OCT 30 1922

Volume VI Number 8

# Journal of the Optical Society of America and Review of Scientific Instruments

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Published Monthly by the
OPTICAL SOCIETY OF AMERICA

OFFICE OF PUBLICATION:
GEORGE BANTA PUBLISHING COMPANY
MENASHA, WISCONSIN

Entered as second-class matter May 31, 1921 at the postoffice at Menasha, Wis., under the act of March 3, 1879.

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Journal
of the
Optical Society of America
and
Review of Scientific Instruments

Vol. VI OCTOBER, 1922 Number 8

# A PHOTO-ELECTRIC THEORY OF COLOR VISION

BY
JANET H. CLARK

## INTRODUCTION

The principal theories of color vision so far advanced, the Young-Helmholz, Hering, and Ladd-Franklin theories, have all assumed photochemical changes in the retina as the basis of vision. This is probably due to the fact that, at the time these theories were formulated, the only known results of the absorption of light energy by matter were the production of heat and the production of photochemical changes. A great deal is now known about another reaction between matter and light, namely the emission of electrons on the absorption of light energy. This phenomenon is called the photo-electric effect. There is the normal effect, seen, usually, only with ultraviolet light, in which the number of electrons emitted increases rapidly with decreasing wave-length of the exciting light. Some substances, the alkali metals, show the selective effect in which the photo-electric current has a marked maximum at some wave-length in the visible. (See Fig. 1.) This selective effect is due to light that is polarized in the E|| plane. The maximum in the curve is, however, still marked when unpolarized light is used as is shown by the curve for rubidium in Fig. 2. The chief facts of photo-electricity are these:—(1)Uniform maximum velocity of electrons for light of a

given wave-length, (2) velocity of electrons independent of intensity of light, (3) number of electrons increases with intensity of light, (4) velocity of electrons increases with decreasing wave-length, (5) in the normal effect the number of electrons increases with decreasing wave-length, (6) with increasing wave-length the effect eventually becomes zero.

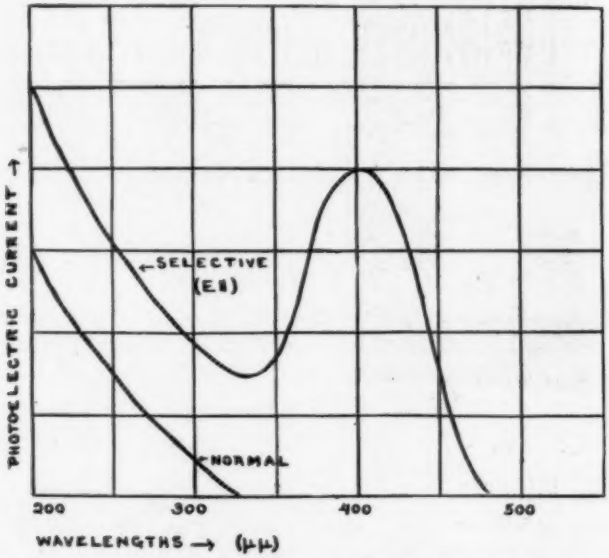


FIG. 1. Typical curves showing the normal and selective photo-electric effects.

Photo-electrons can escape from the surface of an illuminated substance only when the light is absorbed in a surface layer. If it penetrates to any depth, the emitted electrons do not reach the surface and the absorption of light results in an increased conductivity. The electrons may eventually become attached to other atoms or groups of atoms and this redistribution of valency electrons usually results in photo-chemical reactions. I think it can be safely stated that the foundation of all photo-chemical reactions is the emission of photo-electrons on the absorp-

tion of light. This statement is supported by Lewis[1] who says: "At the present time there appears to be a somewhat general tendency to regard photo-chemical reactions as primarily due to a photo-electric effect. The close relationship between photo-electric conductivity and photo-chemical sensitiveness confirms the theory that a loosening of electrons is the immediate cause of photochemical reactions."

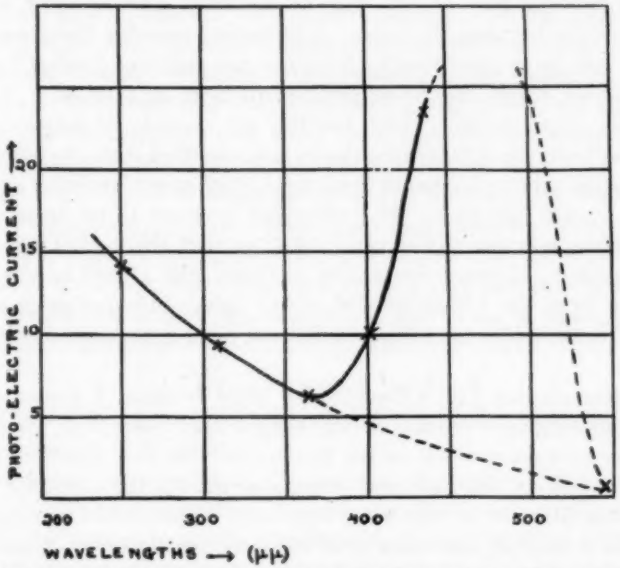


FIG. 2. The photo-electric current from rubidium with unpolarized light, showing the selective and normal photo-electric effects superposed—(from Hughes "Photo-Electricity").

It seems certain then that the photo-chemical theories of vision must eventually be supplanted by a photo-electric one. Several photo-electric theories have been proposed, for the most part by physicists, and have met with little or no encouragement from the physiologists. The most noteworthy of these theories is by Joly.[2]

[1] Lewis, W. C. M., "A System of Physical Chemistry," Vol. 3, p. 134, London; 1918.

[2] Joly, J., Phil. Mag., *41*, p. 289; 1921. Proc. Roy. Soc., B. *92*, p. 219; 1921.

Joly assumes that rhodopsin is the one photo-active substance in the retina and exists in the rods, between the rods and cones, and between the cones in the fovea. It is generally believed that there is no rhodopsin in the fovea, so Joly's fundamental assumption will undoubtedly be denied. However, that does not invalidate his further reasoning. The rhodopsin may be regarded merely ly as a sensitizer for dim lights, playing no part in color vision, and still one may assume that an unknown photo-electric substance lies between the cones. Joly further assumes that there is but one nerve fibril leading from the rod and nine leading from the cone, these nine being grouped in three bundles of 2, 3, 4 fibrils respectively. These bundles are capable of responding respectively to stimulation by electrons emitted from the photosensitive substance around the cones by red, green, and blue light. The energy carried by these electrons is shown to be, from the quantum relation, in the ratio 2:3:4, so that the 2 fibril bundle responds to electrons emitted by red light, the 3 fibril bundle to green light, the 4 fibril bundle to blue light. Stimulation of one fibril in the rod or nine fibrils in the cone gives a sensation of white light.

After reading Joly's theory with great interest, I looked up the histological evidence on the subject and found that Greef,[3] in his exhaustive work on the histology of the eye, mentions no neurofibrils in the rods and cones and doubts the existence of an axial filament in their outer segments. Cajal[4] found no neurofibrils in the rods and cones or in the outer nuclear layer. According to him the first neurofibrils occur in the outer plexiform layer. However, Leboucq[5] gives a detailed description of a system of intracytoplasmic filaments arising near the centrosome at the base of the external segment, spreading out to form the ellipsoid, then condensing into a single filament in the rods and into a bundle of three or four filaments in the cones. So the histological evidence seems to bear out Joly's hypothesis.

[3] Greef, Graefe-Saemisch Handbuch d. gesamten Augenheilkunde, 2 Aufl. vol. 1, ch. 5; 1899.

[4] Cajal, S. R., Internat. Monatschr. f. Anat. und Phys., *21*, p. 369; 1904.

[5] Leboucq, G., Arch. d'Anatomie Microscopique, *10*, p. 555; 1908–09.

The Young-Helmholz theory upheld the doctrine of specific nerve energy, assuming one type of fiber capable of carrying one type of nerve impulse, so that the ending in the brain alone would be responsible for differences in sensation. The Hering and Ladd-Franklin theories assumed that the same nerve fiber can carry two or more types of nerve impulse. Joly's theory assumes that each cone contains three different types of nerve fiber, each capable of carrying only one type of nerve impulse. On this hypothesis he offers an explanation of how one cone can respond to three different stimuli. Nothing is said however of the nature of the nerve impulse itself and there is no explanation of why the sensation of white can be aroused either by stimulation of the one fibril in the rod or of the whole nine fibrils in the cone.

In view of my own difficulties with Joly's very suggestive and interesting theory, I wish to propose another photo-electric theory of color vision which probably has as many difficulties in the path of its acceptance as his, but which I hope will also be suggestive of future developments in the search for a thoroughly tenable and satisfactory photo-electric theory of vision.

## THEORY OF COLOR VISION

The following are the fundamental hypotheses made in the development of the theory:

1. Vision is produced by the emission of photo-electrons from a light sensitive substance occurring in both rods and cones. This substance shows the selective photo-electric effect with a maximum corresponding to the wave-length of maximum luminosity in bright light.

2. Quantitative differences (i.e., differences in luminosity) depend on the number of electrons emitted. Qualitative differences (differences in color) depend on the velocity of the emitted electrons, it being a definite fact that each wave-length causes the emission of electrons with a characteristic velocity.

3. Chromatic vision is possible only in the cones. Rhodopsin, being found in the rods alone, is therefore concerned only with achromatic vision. It acts as a sensitizer to dim lights and, in the presence of the sensitizer, the maximum of the curve of photo-electric sensitivity is shifted to wave-length 535m$\mu$.

In considering the structure of the retina (Fig. 3) it is evident that there is one clear anatomical difference between the rods and cones. Each cone is connected directly to the brain through one nerve fiber, whereas several rods are connected through one fiber. Therefore, if by any means a characteristic disturbance were set up in a cone, it would reach the brain with its character unchanged. But characteristic disturbances starting from several rods and traveling along the same fiber to the brain would undoubtedly reach the brain as a confused disturbance. From the anatomical picture of the retina one would, therefore, expect the cone alone to be capable of chromatic vision.

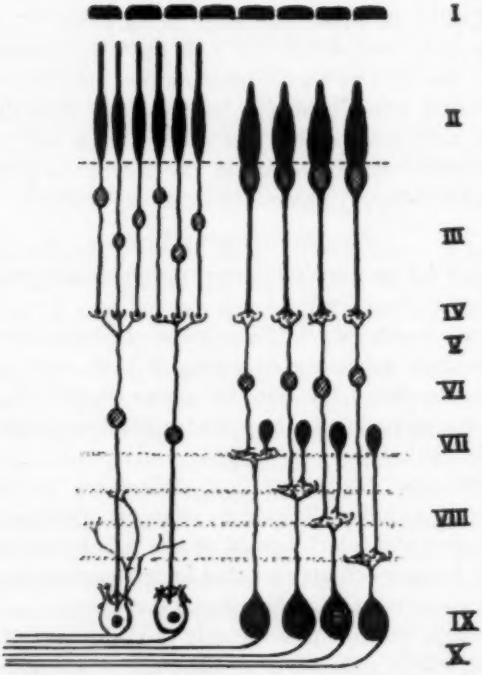


FIG. 3. Schema of the structure of the human retina—I Pigment layer; II rod and cone layer; III outer nuclear layer; IV external plexiform layer; V layer of horizontal cells; VI layer of bipolar cells (inner nuclear); VII layer of amacrinal cells; VIII inner plexiform layer; IX ganglion cell layer; X nerve fiber layer.

A disturbance characteristic of a certain wave-length of light might be set up in the following way. When monochromatic light falls upon the rods and cones they emit electrons with a maximum velocity characteristic of the wave-length of the exciting light. These electrons would move out a certain distance, which Joly (2) calculates to be $5\times10^{-7}$ cm for yellow light. These electrons may be supposed to attach themselves to the molecules of the dielectric medium around the cone and come to rest at a certain distance from the cone, this distance depending on their mean velocity, and therefore on the wave-length of the exciting light. They would, therefore, form negatively charged layers around the rods and cones, which are left positively charged. For this conception I am indebted to Joly's theory of the latent image in a photographic plate (see H. Stanley Allen's Photo-electricity).[6] The layer of negatively charged electrons and the positively charged cone or rod will form the plates of a condenser. When the charge built up is great enough there will be a discharge and a high frequency alternating current will pass to the brain. If the resistance of the circuit is small the current would be oscillatory if great it would be a single pulse. It is immaterial whether there would be oscillations or a single pulse, the important point is that the high frequency current produced by the discharge has a distinct character. The frequency is given by the formula

$$f = \text{frequency} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

where $C$ is the capacity of the condenser, $R$ the resistance of the circuit, and $L$ the inductance. $C$, the capacity of the condenser is different for each wave-length of light, since for each mean velocity of electrons emitted there would be a different distance between the charged layers (condenser plates). Therefore the frequency of the current sent to the brain would be different and specific for each wave-length of exciting light. If now we think of each illuminated rod and cone as a condenser system connected to the brain through a number of spark gaps (synapses), the cone

[6] Allen, H. Stanley, "Photo-electricity," London; 1913.

system will be similar to the diagram in Fig. 4 and the rod system to the diagram in Fig. 5.

If the condenser in a system like Fig. 4B is charged, *a* negative and *b* positive, there will come a point where a discharge will pass across the spark gaps and the condenser will discharge giving a high frequency current. In the cone, Fig. 4A, since each cone

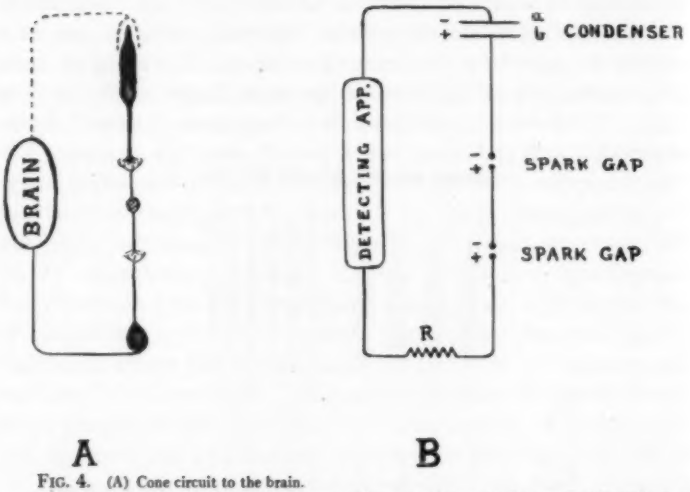


FIG. 4. (A) Cone circuit to the brain.
(B) High frequency circuit containing one condenser, analogous to the cone, and spark gaps, analogous to the synapses in the cone circuit.

is connected directly to the brain through one nerve fiber, the oscillations will reach the brain unchanged for the whole system in Fig. 4B would break down at once sending its characteristic frequency to the detecting instrument. In the rods, where several are connected to the brain through one fiber, conditions are similar to Fig. 5B. In this system condenser I will discharge when the potential difference between its plates is sufficient to break down the resistance of spark gaps 1 and 4, condenser II when it can break down 2 and 4, condenser III when it can break down 3 and 4. Therefore the discharges from the three rods will not pass simultaneously to the brain but will occur irregularly, producing an irregular current made up of the three overlapping frequencies.

Therefore, although one and the same photo-electric substance may be supposed to exist in both rods and cones, their method of connection with the brain makes color vision possible in the cones and only achromatic vision possible in the rods. The rhodopsin may be looked upon as an auxiliary photo-electric substance, existing only in the rods, and active as a sensitizer so that, in its presence, the photo-electricity of the rods is increased and vision

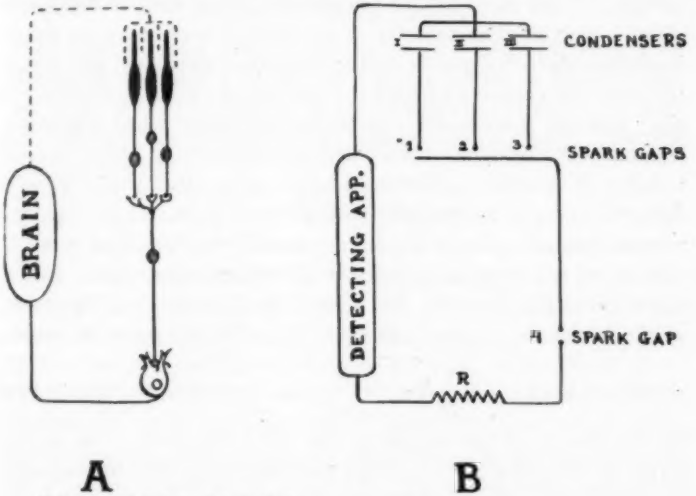


FIG. 5. (A) Rod circuit to the brain.
(B) High frequency circuit containing three condensers in parallel, analogous to the rods, and spark gaps analogous to the synapses in the rod circuit.

in dim lights is made possible. In support of the view that rhodopsin acts by virtue of its photo-electricity, it may be said that Parsons[7] calls attention to the fact that, although rhodopsin is very sensitive to light, it is extremely resistant to the chemical action of strong oxidizing and reducing agents.

This theory as outlined above has, I believe, this strong point. It suggests a mechanism whereby different wave-forms characteristic of monochromatic light may be started in a single cone and

[7] Parsons, J. H., "An Introduction to the Theory of Color Vision," p. 12, Cambridge; 1915.

conducted to the brain along one nerve fiber. Also it definitely suggests that nerve impulses consist of high frequency alternating currents, which may be a series of damped oscillations or, if the resistance is great enough, a single pulse. The time necessary for the propagation of a nervous impulse would, therefore, consist of two parts (1) the time necessary to charge a condenser system sufficiently to break down the resistance of the spark gaps in the circuit, (2) the time for the propagation of an electric oscillation along a nerve. The velocity of an electric wave may be nearly anything, since it depends on the resistance, capacity, and inductance of the system in which it travels and on the sensitivity of the receiving instrument. Short waves, along wires where the resistance is negligible, travel with the velocity of light, but the velocity of electric oscillations along a nerve fiber would be of a different order of magnitude, so that there is no reason why the nervous impulse should not be an electric oscillation or pulse in spite of its relatively slow velocity of transmission. One obvious objection to the theory is this. Since the characteristic frequency of the alternating current set up by the absorption of the monochromatic light is $f=\frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}$ it is necessary to assume that the resistance of the circuit is the same for every cone in the retina in order that the frequency may vary only with the capacity (i.e. with the distance between the layer of electrons and the cone). It is not necessary to assume that the resistance is the same in different individuals. The frequency excited by the absorption of yellow light may $=f_1=\frac{1}{2\pi}\sqrt{\frac{1}{L_1C_1}-\frac{R_1^2}{4L_1^2}}$ for one individual and may $=f_2=\frac{1}{2\pi}\sqrt{\frac{1}{L_2C_2}-\frac{R_2^2}{4L_2^2}}$ for another. So long as it is a definite and characteristic frequency in each individual he will interpret the stimulus as yellow light. It is, however, necessary that the resistance in the path from every cone to the brain should be the same in any one individual, and this may be an unjustified assumption.

Granting this assumption however, this theory is able to explain how different qualities of sensation can be stimulated in one nerve fiber by different wavelengths of light. When it is applied to explain the observed facts of color fusion, color blindness, and after images it is somewhat less successful, but since no theory has been entirely successful in explaining all phenomena, it fares perhaps no worse than the rest.

### POSITIVE AFTER IMAGES

The positive after image is produced by a short exposure with subsequent occlusion of light. It is easily explained by assuming that cones which are charged by the stimulation of light, but have not quite reached the point of discharging, discharge after the occlusion of light.

### NEGATIVE AFTER IMAGES

After stimulation of the retina with strictly monochromatic light the electrons would practically all occupy one layer. It seems safe to assume that there are a limited number of these stable positions possible. If the electrons are stimulated by different monochromatic lights there might be a fairly large number of stable positions possible. If white light is used, giving electrons of many different speeds, probably only a few stable positions would be simultaneously possible. I am inclined to think that it would simplify the whole conception to assume that when electrons of various speeds are emitted they can only occupy two stable positions at a time, there being a number of these coupled layers possible. A certain distance between these stable layers would account for the frequency difference between complementary colors. Then, on stimulation with yellow light containing some white light, most of the electrons would fall into the yellow layer. Those coming off with a slower velocity would be slowed down by repulsion of the yellow layer and fall back into the cone. Those emitted with a velocity great enough to pass through the yellow layer would, after passing through, be accelerated by the repulsion of this layer and take up a position corresponding to the blue layer. A simultaneous discharge from these two layers would give a sensation of yellow mixed with a small amount of its com-

plementary color and the effect would be that of yellow mixed with some white. Owing to the scattered light in the instrument, even spectral colors contain a certain amount of white light.

If it were possible to suppose that one layer might discharge without the other, we might get a sensation of yellow from the discharge of the yellow layer leaving the blue one partly charged. Subsequent stimulation by white would charge up this blue layer further and a discharge would give the negative after image. This does not seem likely and it seems more possible to suppose that, after the discharge of the heavily charged yellow layer, that particular layer would represent a condition of temporary instability so that electrons emitted on subsequent stimulation with white would none of them fall in the yellow layer, but would all fall in its coupled or complementary layer, which would, on discharge, give the negative after image.

### COLOR FUSION

If the retina is stimulated simultaneously by two complementary colors the emitted electrons will fall into two stable layers, and a discharge from the two rings will give a sensation of white. If however the colors are closer in the spectrum than complementary ones, if for instance the retina is stimulated simultaneously by red and yellow, the electrons will fall into one intermediate layer, their two separate layers not being simultaneously stable, and on discharge will give the sensation of orange.

### COLOR BLINDNESS

To explain color blindness one could assume that in some eyes certain stable positions are not possible for the emitted electrons. That red should be most frequently absent is natural since the layer lying nearest to the cone would be the most unstable. The coupled layer for green might be supposed to drop out along with the red. This would amount to assuming a congenital defect in the medium between the cones. A congenital defect in the cones themselves might be a more attractive hypothesis. If, in certain eyes, the photo-active substance in the cones gave a photo-electric curve in which the maximum and the long wave-length limit were both shifted to shorter wave-lengths, the result would be red-

blindness and a shift in the luminosity curve towards the blue. Since the red-blind eye does show a shift in its luminosity curve towards shorter wave-lengths, it seems quite possible that the various types of abnormal color vision are due to abnormalities in the photo-electric emission of the light active substance in the cone.

## COLOR FIELDS

On the foregoing theory one would expect color vision all over the retina (i.e., wherever cones were present). As the cones become fewer and fewer towards the periphery it would take greater and greater intensities of light to stimulate color vision as the stimulus passes outwards from the fovea. It has recently been shown (Ferree and Rand[8]) that the far periphery of the retina is not blind to red, blue and yellow. With stimuli of sufficient intensity the limits of red, blue and yellow coincide with the limits of white light vision.

## EXPERIMENTAL EVIDENCE

Poole[9] has recently investigated the retina for photo-electric activity, and, finding none, considers Joly's theory and all other photo-electric theories of vision untenable. However, in the retina, the escape of electrons under light is not in the surface layer of nerve fibers but down in the rod and cone layer, so that emission of electrons from the surface would not be expected. Evidence should be looked for in a change in conductivity of the retina under light, which would be expected if electrons are emitted from the rods and cones. This is precisely what is shown by the experiments of Einthoven, Sheard, Bovie, etc. (Sheard "Physiological Optics"),[10] in which the current of injury, obtained by connecting the cornea and the cut end of the optic nerve to a galvanometer, is found to undergo a positive variation on exposure to light.

## CONCLUSION

The theory as stated above seems to explain the main facts of color fusion, after images, and color blindness reasonably well,

[8] Ferree, C. E. and G. Rand, *Amer. Jour. Physiol. Optics*, *1*, p. 185; 1920.
[9] Poole, J. H. J., *Phil. Mag.*, *41*, p. 347; 1921.
[10] Sheard, C., "Physiological Optics," Chicago; 1918.

and it does so by means of only one photo-active substance which is undoubtedly a much to be desired simplification.

It undoubtedly explains more satisfactorily than any other theory how different qualities of sensation can be stimulated through one nerve fiber by different wave-lengths of light.

The entire truth in regard to color vision is certainly far from being known as yet but, feeling confident that the correct theory, when found, will be a photo-electric one, I suggest the above outlined theory hoping that it will lead to investigation, criticism, and further speculation towards that end.

SCHOOL OF HYGIENE AND PUBLIC HEALTH
JOHNS HOPKINS UNIVERSITY
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# EARLY PIONEERS IN PHYSIOLOGICAL OPTICS

BY
JAMES P. C. SOUTHALL

Among the ancient Greek philosophers, notably Pythagoras, Empedocles, and Aristotle who flourished in the sixth, fifth and fourth centuries, respectively, before the Christian Era, various theories of vision, all more or less vague and confused, were propounded. According to certain of these conceptions an object was visible by virtue of emanations which it discharged into the eye; whereas another view was that the emanations proceeded from the eye to the object whence they were reflected back into the eye. Whether these emanations were incorporeal or not was a subject of speculation. Pythagoras and his disciples taught that the colour of a body was partly objective and partly subjective, being a concurrent effect of certain peculiarities in the object and corresponding disturbances which these produced in the mechanism of the eye itself; but apparently they were not able to differentiate clearly between the external and internal causes and effects. The only point on which all agreed was that light proceeded in straight lines or rays, and hence the Greek geometers were able to explain the phenomena of shadows and to develop the science and art of perspective representation.

But until the epoch of the great Arabian philosopher Alhazen (*c.* 1100 A. D.) it is hardly possible to speak of a science of vision. The influence of his notions which were singularly clear and correct continues to the present time. In the first book of his celebrated treatise "Opticæ Thesaurus" (which is the title of the Latin translation made long afterwards) Alhazen gives an anatomical description of the eye which is perhaps the earliest detailed account of the structure of that organ. The names which he applied to the various parts of the eye are practically the same as those by which they are called today. He distinguished three transparent fluids or humours, namely, *humor*

*aqueus*, *humor crystallinus*, and *humor vitreus;* and four membranes, namely, *tunica adhærens*, *cornea*, *uvea*, and *tunica reti similis*. Single binocular vision he explained as being due to the fact that the images formed in the two eyes were somehow united and made to overlap in the common optic nerve so as to produce an unique composite impression in the brain itself.

In the historical development of optical science it is difficult to estimate the place of Roger Bacon (1214–1294), because from Bacon's own writings one never can tell whether the extraordinary optical contrivances to which he alludes were actual inventions or merely the exuberant fancies of a very rare scientific imagination and insight into natural phenomena, as seems far more probable. In one place, for example, Bacon tells us of the possibility of constructing an airship (*instrumenta volandi*) whereby a human being sitting in the midst thereof and revolving a mechanism which was attached to artificial wings could ascend from the earth like a bird; with as much assurance as if he himself had actually made such a machine and tested it. Apparently he was acquainted with the use of spectacles which were probably invented about his time, but almost certainly not by Bacon himself.

A very celebrated book which went through many editions and was translated in various European languages was the "Magia naturalis" written by Johann Baptista Porta (1538–1615), who was the inventor of the *camera obscura* which is described in this work.[1] After explaining the principle of the simple pinhole camera, the author proceeds with a certain air of mystery to reveal something marvellous, and tells how when a convex glass lens is inserted in the aperture of the instrument the image depicted on the screen will be so much brighter and sharper than before that it is possible to distinguish the very countenances of the passers-by in the street outside. Porta attached much impor-

[1] The title of the edition of 1591 is: "Jo. Baptistæ Portæ Neapolitani Magiæ Naturalis Libri Viginti, Ab ipso quidem authore ante biennium adaucti, nunc vero ab infinitis, quibus editio illa scatebat mendis, optime repurgati; in quibus scientiarum Naturalium divitiæ & deliciæ demonstrantur. Accesit Index, rem omnem dilucidè repræsentans, copiosissimus. Francofurti, Apud Andreæ Wecheli heredes, Claudium Marnium & Joann. Aubrium. MDXCI."

tance to the manifold applications of this invention; and then he adds significantly: "There can be no doubt that the human eye is such a *camera obscura* into which the light comes from outside; the pupil acts like the aperture in the window-shutter, and the crystalline lens performs the office of the white wall or screen" on which the image is cast. The analogy here suggested is indeed very striking, but it is hard to see how, knowing the action of lenses as he did, Porta could have supposed that the ocular image was completed in or on the crystalline lens.[2]

In another one of his books, namely, "De refractione,"[3] published in 1593, Porta again compared the eye with a *camera obscura;* and also called attention to the contraction of the pupil in bright light and to its dilatation in feeble illumination. However, this important observation had been mentioned by Leonardo da Vinci (1452–1519) apparently as a well ascertained fact in his time. A certain Fabricius ab Aquapendente, who was very nearly contemporary with Porta, relates that Fra Paoli Sarpi had communicated to him the fact that both pupils are affected simultaneously in the same way depending on the degree of illumination. Concerning singleness of binocular vision, Porta inferred that only one eye was used at a time and that, somewhat after the manner of birds, the right eye was employed when the object was a little to the right and the left eye when it was to the left.

The subject of colour was another matter which greatly interested Porta and which he says he had studied with much curiosity for more than forty years, although it was so intricate and difficult as to be almost beyond mortal ken. No wonder the poets had called the many-coloured rainbow the daughter of Thauma! But Porta believed he had at last found some clues to this mystery also.

[2] According to Porta the seat of vision had to be between the pupil and the centre of the eye where the visual rays from the various points of the object intersect, if the object was to be seen erect; and consequently he inferred that the seat of vision was in the crystalline lens, which, as he says, is "extra oculi centrum."

[3] "Joan. Baptistæ Portæ Neap. de Refractione, Optices Parte Libri Novem. Ex officina Horatij Salviani. Neapoli. Apud Jo. Jacobum Carlinum & Antonium Pacem, 1593."

Among the pioneers in physiological optics the name of Franciscus Maurolycus (1494–1577) deserves a place chiefly on account of one of his numerous writings called "Photisimi de lumine et umbra" published near the end of his life in 1575. It is only a small volume but it contains several discoveries which are important in the theory of optics. Incidentally, Maurolycus seems to have been the first to show that a ray of light issues from a transparent isotropic plate bounded by plane parallel faces in the same direction as it was going before it entered. He gave also an explanation of the circular arc of the rainbow and distinguished in it four principal colours which he called *croceus* (yellowish like saffron), *viridis* (green), *cæruleus* (sky-blue), and *purpureus* (purple), together with three other colours which he regards as transitions or *connexiones*. It is usually stated that Newton was the first to distinguish seven colours in the prismatic spectrum.

Knowing only the general effect of glass lenses as convergent or divergent, Maurolycus deserves much credit for being the first to explain the action of the crystalline lens in the human eye by analogy with artificial lenses; and although he assumed (like Porta) that the image in the eye must be erect since that was the way the object appeared, he was at least nearer the truth in insisting that the rays were not converged in the crystalline lens itself, but beyond it. From the fact that a far-sighted eye requires a convex correction-glass, Maurolycus argued that the curvature of the crystalline lens in an eye of this kind was not sufficient, whereas in a near-sighted eye it was too great.[4]

But it was Kepler (1571–1630) who, far in advance of his predecessors, began to formulate clear and precise notions as to the *modus operandi* of the eye and the science of vision. In his famous treatise known as the "Supplements to Vitellio,"[5] which in spite of

[4] Another work on optics by this same author written in 1553 but apparently published many years after his death has the following title: "R. D. Francisci Maurolyci Abbatis Mersanensis mathematici celeberrimi Diaphanorum partes seu libri tres; in quorum primo, de perspicuis corporibus; in secundo, de Iride, in tertio: de organi visualis structura, & conspiciliorum formis, agitur. Lugduni Apud Ludovicum Hurillion, MDCXIII, cum privilegio."

[5] "Ad Vitellionem paralipomena; quibus astronomiae pars optica traditur, etc." Frankfurt, 1604. (The writer has recently seen an extract from a letter by Dr. M. von Rohr stating that he is preparing a German translation of this noteworthy volume.)

certain manifest faults and obscurities is a work of great originality and importance, Kepler gives a minute description of the anatomical structure of the eye. The *cornea* is the transparent and more convex portion of the tough outer coating of the eye called from its hardness the *sclerodes tunica*. The anterior side of the *sclerodes* and even the *cornea* itself are contained in a very thin transparent membrane called the *tunica adnata* or *adhærens*. The posterior dark-coloured side of the second coating of the eye with its numerous arteries and blood-vessels constitutes the *choroides tunica*, while the anterior part on the outside forms the *iris* diaphragm with its central round window or pupil. The third coating is the *retina* on which the images of external objects are focused. The *humor crystallinus*, contained between the *humor aqueus* in the anterior and the *humor vitreus* in the posterior chamber of the eye, is suspended in a transparent capsule called *aranea* (*arachnoides*) *tunica*, whereas the vitreous humour is enclosed in the *hyaloides tunica*. No special capsule is provided for the aqueous humour which is comprised between the *cornea* and the *aranea* and the *processus ciliares*. These latter proceed from the *uvea* on the posterior side of the membrane whose front surface is the *iris* and form a kind of radial collar surrounding the crystalline lens.

Kepler is very explicit about the retina (*retiformis tunica*) as the surface on which the optical image in the eye is projected. This "reddish white" surface he supposes to be a portion of the inside of a hollow sphere, which acts like a screen (*papyri vice*) for receiving the image and partly surrounds the crystalline lens. Thus he says that the pupil is the common base of cones of incident rays emanating from the various points of the object, and that these rays emerge finally from the crystalline lens converted by refraction into bundles whose vertices lie all on the retina where consequently a small inverted image resembling the object is depicted point by point. So firmly was Kepler convinced of the essential correctness of this theory that he affirmed that if the other membranes of the eye could be removed so as to expose the transparent retina from behind, an observer might see traced on it a minute image of the external field of view. The experiment

which is here suggested was actually made some years later by Kepler's contemporary, Christoph Scheiner, who cut a hole in the upper sclerotic coating of a freshly enucleated eye and then removed all the opaque portions whereby he was enabled to perceive the image of a luminous object focused on the retina. These experiments were made first with the eyes of sheep and oxen, but later in 1625 in Rome Scheiner performed the same experiment with a human eye.[6]

Kepler's later book on "Dioptrics,"[7] which is as distinguished for its logic and clearness as the "Supplements to Vitellio" is lacking in these respects, likewise contains many acute and original speculations in regard to the process of vision. By this time Kepler was so certain that it was necessary for a sharp image to be focused on the retina in order for the eye to see distinctly, that he inferred that the posterior surface of the crystalline lens must be hyperbolic in form instead of spherical; although unless the rays inside the lens were parallel to the axis it is difficult to see what particular advantage is to be gained by an hyperboloidal rear surface. But it is worth noting here that Kepler anticipated Descartes in conceiving of an aspherical lens for uniting a bundle of rays exactly in one point.[8]

In Prop. LXI of the Dioptrics Kepler asserts that vision is a sensation stimulated in the visual substance ("Sehgeist" or "plena spiritus") which he conceives to form a sort of sensitive layer over the surface of the retina. The coloured delineation of the external world which is traced on the retina by the action of the optical system of the eye on the rays of light which come into it is, according to Kepler, not a mere superficial effect like that of light playing over the surface of an ordinary screen or wall, but it is a selective and penetrating influence which produces some change or photochemical action (as we would say) in the visual

[6] See Caspar Schott's "Magia universalis naturæ et artis" (Würzburg, 1657), p. 87. Also, Dr. Joseph Priestley's "Geschichte und gegenwaertiger Zustand der Optik," Klügel's German edition (Leipzig, 1776), p. 93.

[7] "Johannis Kepleris, Sæ. Cæ. Mtis. mathematici Dioptrice. Augustæ Vind., 1611" (small quarto, 79 pages). See also "Johannes Keplers Mathematikers Sr. Kaiserlichen Majestaet, Dioptrik," Nr. 144, Ostwalds Klassiker, Leipzig, 1904.

[8] See "Dioptrik," Props. LIX, LX, pp. 27, 28.

substance contained in the retina. Kepler says he was led to infer this from the nature of light itself which, when it is powerful and concentrated, has so-called focal properties and may even cause combustion; and so he argues that between the comparatively minute quantities of light which in the eye are directed towards the delicate fine-grained structure of the retina there is the same connection in kind as exists outside the eye when a beam of sunlight is focused on the ordinary gross matter of an inflammable body. In support of this conception he alludes to the case where the eye has been fatigued and strained by being exposed to a bright illumination, sometimes to such an extent that even when the source of excitation has been removed a strong after-image of it persists for quite a time; indicating that the impression made on the retina must have been a curiously deep-seated effect. These remarkable opinions which anticipated Boll's discovery of the so-called visual purple by more than two centuries and a half bear testimony to Kepler's original and remarkable genius.

But the impression produced on the retina is by no means the whole of the visual act, and Kepler explains that this sensation has now to be transmitted to the brain in an unbroken current where it is communicated to the centre of consciousness. However, owing to the imperfect state of the knowledge of the anatomy of the nerves and the brain in his day, Kepler was not able to form an entirely correct picture of the actual route of transmission from the organ of vision to the visual centre of the brain. He wonders also if perhaps the subtle visual material which he assumes to be spread over the retina is itself conveyed along the optic nerve from the eye to the brain.

On the other hand, Kepler was obviously at a loss in trying to explain why objects appear to be erect although their images on the retina are inverted. He touches on this question in the "Supplements to Vitellio" and uses some metaphysical language about "how the passive must lie opposite to the active," and adds that the movements of the eye enable us to distinguish the top of an object from the bottom, since the eyes must be directed upwards towards a lofty monument or downwards in gazing at the sea from a high cliff.

Without being aware of the previous speculations and hypotheses of Maurolycus concerning near-sight and far-sight, Kepler finds the explanation of these defects in the fact that the length of the eye is either too great or two small (axial ametropia); as Scheiner believed also. In a near-sighted (myopic) eye the rays are focused in the vitreous humour and produce blur-circles on the retina; whereas in a far-sighted eye the rays are not bent enough and are focused therefore beyond the retina, producing blur-circles on it as before. Kepler guesses that in either case, assuming the eye to be otherwise normal, the trouble is due to the mode of life and occupations of the individual and not to any natural or inherent defect. Elderly folks are usually far-sighted or presbyopic because they are feebler than in youth and because it is easier and more natural to maintain the axes of the two eyes parallel than to turn the eyes inwards in order to see near objects distinctly.

According to Kepler, a perfectly healthy eye has the faculty of seeing equally well both near and far. On the other hand, when a person is quite unable to see anything distinctly, there is some pathological or diseased condition of the eye which may be partial or total blindness (Prop. LXIV of the Dioptrics). He supposes that accommodation is produced by varying the interval in the vitreous humour between the crystalline lens and the retina until the image is sharply focused on the latter, whether the object in question be far or near. Just as it is possible to vary involuntarily the size of the pupil depending on the degree of illumination, Kepler believed also that the eye could be stretched equatorially so as to shorten the eyeball and reduce the interval between lens and retina; or, conversely, that the eyeball could be elongated by equatorial contraction so as to increase this interval. The seat of this mechanism was supposed to be located in the web-like structure which supports the crystalline lens and connects it with the uvea by the dark radial branches called the ciliary processes, which appear to be formed like a comb to enable each muscle to act by itself. When all these muscles contract together and are shortened, the pupil becomes smaller and at the same time the lateral parts of the eye are drawn inwards while the eye-

ball as a whole is elongated. The reverse process occurs when the ciliary processes are lengthened.

Concerning binocular vision, Kepler says (Dioptrics, Prop. LXII) that when the retinas of the two eyes are stimulated in equal fashion, the two images are fused and the object is seen single; whereas under unequal stimulation fusion does not take place and the object appears double. Again, in the "Paralipomena," Kepler explains that it is by an unconscious process of triangulation in which the distance between the two eyes is the constant and essential factor that we are enabled to form more or less imperfect estimates of distance; and he even suggests that for very short distances a similar method may serve in the case of monocular vision, the fundamental base-line being the diameter of the pupil itself. However, this latter observation would appear to be rather far-fetched, not merely on account of the comparatively small dimensions of the pupil but particularly also because these dimensions are variable.

Another remarkable man of this epoch whose name has been mentioned already and who ranks alongside of Kepler as one of the founders of physiological optics was Christoph Scheiner (1573–1650). A professor in one of the colleges of the Society of Jesus in Germany, he rose to high eminence in the councils of that great religious order. While he was still only a student of mathematics at Ingoldstadt, he read with eagerness the Sidereal Messenger in which Galileo announced those wonderful astronomical discoveries that excited such a fierce controversy through all the learned world of that day. Partly owing to his naturally prudent temperament but perhaps more to his religious training and associations, Scheiner did not espouse the Galilean philosophy and points of view with the same ardour as his countryman Kepler; and yet he was one of the first to extend those new methods in physics and astronomy, with so much industry and ability that his name will always be called in company with the most illustrious men of that notable era in the history of the intellectual development of Europe. Strange to say, his remarkable achievements have remained comparatively unknown.

When Galileo began to publish his discoveries in 1610, there were only a few telescopes available in Germany. Kepler himself had not been able to get a glimpse of the "Medicean Stars" until August 30, 1610. But Scheiner immediately procured or made for himself a number of these new instruments, and in his first scientific announcement he speaks of having as many as eight "tubes" of different proportions. Kepler described in his Dioptrics the optical construction of the astronomical telescope which is today called by his name, but as his peculiar genius lay rather in conceiving than in executing it is doubtful whether he ever saw an actual instrument of this type. Scheiner, on the other hand, possessed unusual mechanical ability and ingenuity, and undoubtedly it was he who constructed the first astronomical telescope composed of a combination of two convex lenses, probably about 1614;[9] although Rheita in a book entitled "Oculus Enoch et Eliæ" (1645) claims to have been the first to have made a telescope according to Kepler's description. Scheiner also constructed for Duke Maximilian of Tirol a so-called terrestrial telescope composed of three convex glasses which gave a magnified erect image of distant objects.

Scheiner was indeed a prodigious and indefatigable worker and his writings cover a wide range of subjects. Several years ago Dr. von Rohr to whom modern optical science is indebted for so many valuable contributions and extensions of our knowledge, edited and published a German translation of selected portions of Scheiner's very original and noteworthy treatise entitled "Oculus sive fundamentum opticum,"[10] the first edition of which was issued at Innsbruck in 1619. A third edition was published in London in 1652 after Scheiner's death. It is only possible to give here an exceedingly brief and necessarily very inadequate summary of the general character and main conclusions of this volume which, composed more than three centuries ago, was perhaps the first formal treatise on physiological optics. The entire work is

[9] See Scheiner's "Rosa Ursina," Bracciani, 1626–1630.

[10] Ausgewählte Stücke aus Christoph Scheiners Augenbuch; übersetzt u. erläutert von M. von Rohr: *"Zft. f. ophthalm. Optik, 7,* pp. 35–44; 53–64; 76–91; 101–113; 121–133; 1919.

divided into three principal parts, the first of which contains a kind of *résumé* of what was known at that time concerning the eye and vision, more particularly as to the anatomy of the eye with an account of various related experiments; the second part is concerned with the manner of the refraction of light and the procedure of the visual rays in the eye itself; while the last part treats particularly of vision and the appearances of objects. The most striking characteristic is the consistent use of the method of observation and experiment which Scheiner employs to explain and support his hypotheses and opinions.

He succeeded in obtaining at least an approximate measurement of the curvature of the cornea by observing the image of a window or other suitable object reflected therein and comparing this appearance with the similar image seen in a small glass sphere placed as near the eye as possible on the temporal side. A number of little glass marbles or bulbs of various sizes enables the experimenter to select by trial that one which shows an image of the object as nearly as possible equal to that which is reflected in the cornea and thus to compare the curvature of the latter with the known curvature of the test globe.

That Scheiner was an accurate and painstaking observer is abundantly manifest. He noted the minute forward displacement of the pupil in the act of accommodation; together with the fact that accommodation is invariably accompanied by a modification of the diameter of the pupil. .As to the ciliary processes, he supposes that these muscles are capable of tension and relaxation perhaps for the purpose of producing a slight alteration in the total length of the eyeball in the process of accommodation. With singular acumen he suggests that there may be likewise a concomitant change in the form of the crystalline lens itself This seems to have been the first conjecture of the essential factor in accommodation as Thomas Young endeavored to prove long afterwards (1793). Certainly, there is no allusion to it in Kepler's writings.

In order to explain the procedure of the visual rays inside the eye and how the image is formed on the sensitive retina, Scheiner devised numerous simple and ingenious experiments, models of

their kind, some of which indeed have become classic. He was particularly fond of stenopæic tests of various kinds; one of which, usually referred to as "Scheiner's Experiment," is still to be found in modern text-books on physiological optics. In another experiment he shows how distant objects will generally be seen double when they are viewed through two pinhole apertures in a cardboard held close to the eye, provided the interval between the holes is less than the diameter of the pupil. In fact, there will be as many images as there are pinholes comprised within an area of the card not greater than that covered by the pupil of the eye. By the help of these simple devices he was able to trace the general procedure of the visual rays without knowing the precise law of refraction.

Entoptic phenomena and likewise the curious effects of irradiation receive much attention in Scheiner's book. He endeavors to explain why a piece of white-hot iron appears to be about three times as large as when it is cool; which leads Dr. von Rohr to comment that Leonardo da Vinci had also observed that part of an iron bar heated to incandescence appeared thicker than the cold portion.

Scheiner devised also a simple experiment for locating approximately the position of the pivot or centre of rotation of the eye. Finally, he was at some pains to determine the refractive powers of the various ocular media, reaching the conclusion that the aqueous humour and the crystalline lens act nearly as if they were composed of water and glass, respectively; whereas he inferred that the refractive power of the vitreous humour was intermediate between those of the other two.

The process of vision as expounded by Descartes (1596–1650) seems to be based on the views of Kepler and Scheiner with whose writings he was undoubtedly familiar, although he makes little, if any, allusion to either of these authors. For an extremely interesting account of Descartes' opinions on this subject the reader is referred to the first section of a paper by J. W. French entitled "The unaided eye," published in the *Transactions of the Optical Society* (London), XX, pp. 209–236 (1919); which contains a translation of Descartes' description of the human eye taken

"from the work entitled *Renati Descartes Opera Philosophica* dated 1656," together with *facsimile* reproductions of two of the original diagrams.

When Christiaan Huygens (1629–1695) began his famous work on Dioptrics in 1653, which was never completed and which was published first in more or less fragmentary form a few years after his death and again recently in a complete annotated edition in both Latin and French,[11] the keenest scientific minds of that day were concentrated on the phenomena of light and vision. The law of refraction had at last been discovered. Huygens' contributions in the domain of physiological optics are perhaps not generally known, especially as they are to be found scattered here and there in the main body of the "Dioptrica," but in the aggregate they form a considerable mass of solid achievement in this field. Huygens indeed touched nothing which he did not adorn, and he was never satisfied until he had gotten to the bottom of the matter. His admiration of the marvellous mechanical construction of the eye and its adaptation to human needs frequently breaks forth in some of the most eloquent and famous passages of this work. In the first part of the Dioptrics[12] and afterwards in the article "On the eye and vision,"[13] Huygens gives a description of a "simplified eye" formed of two concentric hemispheres one of which has a radius three times as great as that of the other. They are placed in juxtaposition with their flat surfaces in contact. The curved surface of the smaller hemisphere represents the cornea, while that of the other portion represents the retina or rather the choroid which Huygens was inclined to regard as the seat of vision.[14] The entire cavity inside the two superposed hemispheres is supposed to be filled with an aqueous

[11] "Christani Hugenii Zelemii, dum viveret, Toparchae Opuscula Postuma, quae continent Dioptricam. Commentarios de Vitris Figurandis. Dissertationem de Corona & Parheliis. Tractatum de Motu. De Vi Centrifuga. Descriptionem Automati Planetarii. Lugduni Batavorum, Apud Cornelium Boutesteyn, 1703."

"Œuvres complètes de Christiaan Huygens publiées par la Société Hollandaise des Sciences. Tome treizième. Dioptrique. 1653; 1666; 1685–1692. La Haye, Martinus Nijhoff, 1916."

[12] Œuvres complètes, Tome XIII, pp. 128–134.

[13] *Loc. cit.*, pp. 787–802.

[14] *Loc. cit.*, p. 795.

humour of refractive index $\frac{4}{3}$; the actual dimensions being of no particular consequence but the relative dimensions such that rays of light proceeding from a distant object-point and undergoing refraction at the transparent surface of the smaller hemisphere will be accurately focused on the inner surface of the larger hemisphere. In order to get rid of the faults of spherical aberration as much as possible, Huygens provides also something in the nature of a pupil by making the plane surfaces of the two hemispheres opaque where they are in contact except for a small circular area right around their common centre. Huygens' simplified eye, as above described, bears a striking resemblance to the so-called "reduced eye" conceived long afterwards by J. B. Listing.[15] In both cases the optical system of the eye is replaced by a single spherical refracting surface with its centre at the nodal point of the eye, the relative index of refraction being $\frac{4}{3}$. But while the geometrical similarity of the two conceptions is well-nigh perfect the purposes for which they were devised were quite different. Listing's "reduced eye" was intended merely as an aid to oculists and ophthalmologists for the simplification of their calculations and constructions; but Huygens' aim was primarily to study the essential *modus operandi* of the actual eye with its pupil in place; and afterwards he is careful to point out how inferior this crude contrivance is to the marvellously delicate and adapted mechanism of the living eye. Subsequently, in 1691, when, partly in consequence of certain careful ophthalmic measurements made by the physician Pecquet in 1667 in his presence, Huygens was more familiar with the actual dimensions of the human eye, he described a "schematic eye" which more nearly represented the optical system of the actual eye,[16] but which was considerably more complicated than his original "simplified eye."

As to the mechanism of accommodation, Huygens supposed that this power might be produced by a forward movement of the crystalline lens or by an increase in the convexity of the lens (as Scheiner had imagined) or by a combination of both of these

[15] Beitrag zur physiologische Optik (Göttingen, 1845), pp. 16–18.

[16] *Loc. cit.*, pp. 800–802.

causes.[17] At the time of Pecquet's measurements referred to above he was struck with the flexibility of the crystalline lens and how its form changes under the pressure of the fingers,[18] and hence he concluded that the act of accommodation was effected by a change of curvature of the lens. Subsequently, however, in 1670 he returned again to the explanation of the forward movement of the lens without change of form.[19]

Another thing which constantly excited Huygens' admiration was the contrivance of the pupil of the eye which remained always circular in form whether it was big or little.

He was an empiricist concerning the old question as to how we see objects erect when their images on the retina are upside down. Our judgments of appearances, he says, are largely a matter of habit, and even if everything had to be viewed through a glass which inverted them, we should still speak of seeing things erect and should experience no difficulty in pointing to the top or bottom of an object.[20]

Huygens found the ideas of myopia and presbyopia in Kepler's writings, and he formulated very definite rules for determining the powers of lenses for the correction of these defects of vision.[21] It is interesting to compare his way of treating these problems with that of Barrow (1630–1677) in his lectures on Optics.[22]

Concerning emmetropia also Huygens says "there is nothing in nature which shows the geometry of the Creator more than the eyes" and it is indeed "admirable that the surfaces of the cornea and the crystalline lens are just of that degree of convexity to bring parallel incident rays to a focus in the fundus of the choroid. Perhaps it is different in the case of little children who may be able to adjust their eyes in some manner; but that is also no less marvellous."[23]

[17] *Loc. cit.*, p. 133.

[18] *Loc. cit.*, p. 789.

[19] *Loc. cit.*, p. 794.

[20] *Loc. cit.*, p. 745; also p. 829.

[21] *Loc. cit.*, pp. 134–138.

[22] "Lectiones XVIII Cantabrigiæ in Scholis publicis habitæ in quibus opticorum phenomenon genuinae rationes investigantur, ac exponuntur. Etc. Ab Isaäco Barrow. Londini, MDCLXIX." Pp. 102, 103.

[23] *Loc. cit.*, p. 756.

Notwithstanding that there is an image formed in each eye, Huygens tells us that Nature has taken particular pains to prevent us from seeing double; for each point in the fundus of one eye has its "corresponding point" in that of the other eye, and it is only when an object-point is imaged in a pair of corresponding points in the two eyes that it is seen single as it really is.[24] These corresponding points according to him lie both on the same side of the optic axes and similarly placed with respect to the two optic nerves; and hence it is plain that a distant object will be seen double when the eyes are converged on a nearer one, and *vice versa*. Huygens' theory of corresponding points on the retinas of the two eyes is indeed as complete as that to be found in modern text-books. Robert Smith (1738) in his "Compleat System of Opticks" entertains exactly the same views, and he observes also that Leonardo da Vinci had explained how the most accurate painting can never give a plastic impression of relief as perfect as that which is obtained from looking at real objects, because the images of a solid object in the two eyes are necessarily somewhat different. If Huygens had only recognized this fact clearly, he might have anticipated Wheatstone (1838) in the invention of the stereoscope.

The secure foundations of the science of physiological optics were laid principally by the genius and penetration of Kepler, Scheiner, and Huygens. It was chiefly through their labours in this field that their great successors, Young (1773–1829), Donders (1818–1889), and Helmholtz (1821–1895),—to mention only a few of the most illustrious names—were enabled to develop and extend the theories of light and vision in all their manifold ramifications with other branches of human knowledge.

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NEW YORK, N. Y.
JUNE 1, 1922.

[24] *Loc. cit.*, p. 796.

# INSTRUMENT SECTION

## THE MECHANICS OF OPTICAL POLISHING

BY
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The problem of how it is that, for example, a glass surface which has been smoothed or finely ground can, by proper means, be polished not only so as to be invisible ordinarily, but so that under the severest tests it shows no diffusion of light (as of the sun's rays falling on it) has at times engaged the attention of the ablest physicists. The late Lord Rayleigh studied the matter and his paper[1] on the subject is well known. He properly explains the polishing process on the principle of removal, by a process similar to grinding, of the high points of the surface, and progressively so until the whole ground surface has been cut away, but the cutting is by an action so fine that the grain produced is beyond the power of resolution by a microscope or other powerful optical means.

It is the purpose here to show that while this view is measurably correct it does not go far enough, and that the polishing is a unique mechanical process; a self regulated planing down of the surface to a real level without even the finest scratches or other character which would lead to diffusion of any light falling on the surface.

Some have most erroneously tried to explain the result of the process, by assuming that the glass has, during the polishing, actually flowed; or that there was some peculiar plastic condition brought about which allowed the glass surface being polished, to take on the characteristics of a liquid surface. There is no need for such hypotheses and no validity in such assumptions. This will be made clear.

In burnishing of plastic metals by a hard burnisher, there is, of course, such flow, but with hard, brittle, non-malleable materials like glass, the process is decidedly not like burnishing.

[1] Lord Rayleigh, Proc. Roy. Inst. Gr. Britain, March, 1901; Trans. Opt. Soc. *19*, October, 1917.

Glass may receive an optical polish in either the wet or dry way. Other materials of a brittle, non-malleable nature are dealt with similarly; such are quartz, agate, calcspar (Iceland), and many jewels and minerals.

In the manufacture of plate glass, the ground surfaces (the last, or smoothing stage, being often called *mud ground*) are not worked by grinding to so fine a grain of surface as in the better class of accurate optical work, and the polishing is done by runners of felt charged with rouge (crocus) and water moved over the plate by machinery. The result is that the surface obtained is not an optical one; it has a smoothness and polish similar thereto, but is wavy throughout, as can easily be discerned by a skilled eye in regarding the reflection of an edge from such surface; and, of course, by other simple tests. It is neither optical in the large or in small elements of surface. The yielding felt runners have swept out indiscriminately the hollows, small and large, and have not held the surface to a definite figure. Similar yielding polishers are used in finishing the very irregular surfaces of cut glass. The cheaper kind of lenses, where accuracy of figure is not needed, are often cloth polished, a process which, if carefully conducted, gives a result intermediate between the plate glass surface and the true optical surface, such as is obtained by a pitch polisher with rouge and water. The considerations as to the true nature, the mechanics, of the polishing process are applicable to all such cases, but will be given in connection with the pitch polishing, most usual in good work. They apply, too, to the case of dry or paper polishing with paper faced tools charged with tripoli (diatomaceous earth) a method of polishing which has been used to some extent in France for medium grade lenses.

In rouge polishing with pitch for a carrier, as is usual, the surface of the pitch is moulded to fit the glass and is divided (usually) into small square facets by grooving. It is worked over the glass, or the glass worked upon it by movement in all directions or such innumerable paths are given that no definite course is repeated. This is essential to the best result.

The conditions as found, in successful work, are as follows. The rouge, though very hard, is friable and breaks down to a very

fine powder. Too hard (non-friable) rouge will tend to fine scratches. These scratches are not like grinding or crushing, but are smooth bottomed grooves, discoverable by a magnifier.

The pitch is at all times yielding. It is made so by tempering and testing. If too hard, it tends to cause fine scratches, all over the surface which is being polished. These, with very hard pitch, may resemble grinding, but ordinarily they show no crushing, but are smooth cuts.

In grinding, on the contrary, the surface is crushed, while in polishing it is clean cut. Smooth cutting is the rule. The polishing is indeed a kind of planing process; the particles of rouge set themselves into the pitch surface and cut smoothly; they do not roll or grind. There are millions of fine planing or cutting edges at work fixed in position by becoming, at least temporarily, embedded in the pitch surface, which readily yields to receive them. They make smooth cuts as can readily be seen by examination of the scratches when the pitch is overhard or the rouge too hard and nonfriable. Good rouge is friable without apparent limit, and rouge washed out of a used polisher may be so fine as to float for days in colloidal solution.

All the above considerations are fairly well known and recognized, but there is one additional condition, or circumstance, which, so far as the author knows, is worthy of record, no attention having been hitherto drawn to it.

It is this: by the very nature of the case the particles which are doing the cutting in polishing are all *automatically adjusted*, in successful work, to cut to the *same depth* during any stroke. The yielding nature of the pitch surface not only ensures this, but makes it a necessary consequence, for any particle of rouge riding higher than another is at once depressed to the proper level by sinking into the pitch surface. The innumerable cutting edges of all the particles reach a common level, and with motion of the polisher in all directions, and cutting smooth (no crushing or grinding) the result cannot fail to be what it is, an optical surface without grain or irregularity. The rouge is friable without limit, so that the polishing particles may, in the process, become finer and finer. With felt, cloth, or paper as a carrier for the

polishing powder, the effect is much the same; the particles are held to position when cutting, as planing tools. Even fine washed carborundum will polish glass if held in the surface of soft wood or cork, and the author has even produced a fair polish on a glass lens by a soft metal tool charged with fine carborundum. In such case, the polishing takes place in a few seconds, but the technical difficulties are very great. In dry polishing, a sheet of paper is pasted down on the surface of the polishing tool, and a special high grade pure paper, rather heavy and uncalendered, is used. This is charged by gently rubbing its surface with a lump of fine tripoli selected for the purpose, the fine silicious skeletons composing which constitute the polishing powder. The first application to the smoothed surface, as of a lens, which surface has the fine grain usual in such a case, is to show innumerable fine scratches, criss-crossing in every direction. They are, however, smooth scratches. As the work goes on, the tripoli works down to finer and finer conditions, while the polishing comes up gradually, no new application of the powder being required after the start. It is manifest that here too is the condition of smooth cutting and particularly a self adjustment of cutting depth, owing to the yielding character of the paper surface, so that at the end all the cutting is done in one surface of movement. It is believed that this dry paper process is much less used than formerly. It cannot be expected to yield the high accuracy that may be obtained with the wet pitch.

It is thought that in pointing out the mechanics of the polishing process, and more especially the smooth cutting and self-adjustment of cutting particles above described, the interesting process of the production of an optical surface may be relieved of something of the mystery which has been its accompaniment.

The author has drawn upon an experience of more than fifty years in occasional working of optical surfaces on glass of many kinds and on media, such as crystal quartz and fused quartz, Iceland spar and others.

The amount of material removed from the surface under treatment, is, of course, seen to be almost infinitesimally small per stroke, and it is only by the long continuance of this action that

at last there is a sufficient removal to secure an optical surface. Time is saved by carrying the fine grinding or smoothing as far as possible before applying the polisher. As Rayleigh has stated, and it is of course the common experience, polishing begins on the highest or most elevated parts of the surface, seen only under a magnifier, and these are removed while the polished spots widen out, and, if the surface has been well prepared, or *bottomed*, as it is termed, spread to include the whole surface. If the surface has not been well bottomed, there will remain pits which the slow planing action of the polisher is incompetent to remove in reasonable time, and if the polishing is continued too long, the surface is more than likely to have lost its truth, or has been seriously deformed. This, however, depends on the polisher itself keeping its form. Too soft pitch is a guard against polisher scratches from particles of grit, but not conducive to accuracy. Accuracy can be helped by remolding the polisher at intervals by slight warming of its surface and application to a true surface of the same character as that being produced, while moistening the said surface to prevent adhesion.

No matter what degree of smoothness has been attained in polishing, the continued smooth removal of the glass surface goes on as long as there is rouge, pitch and water applied; a fact which is, of course, taken advantage of in parabolizing a concave astronomical glass mirror.

GENERAL ELECTRIC CO.
LYNN, MASS.
JULY 20, 1922

# A VARIABLE RESISTOR OF LOW VALUE[1]

BY
C. N. HICKMAN

In making electrical measurements there is often a great need for a continuously variable resistor of low value. Variable resistors consisting of a copper wire sliding in an insulating tube containing mercury[2] have been used in the Resistance Measurements Section of the Bureau of Standards for several years. The Inductance and Capacitance Section has constructed a number of them with a surrounding copper tube on which the current returns, thus decreasing the inductance of the circuit.

These instruments are very useful for varying the resistance of a circuit provided the current is small. However, they cannot be used when the value of the resistance must be known with a high degree of accuracy on account of the high temperature coefficient of mercury. Also, where careful measurements are being made, the continuous change of resistance due to heating makes a mercury resistor unsuitable for carrying large currents.

The resistor described in this paper is a modification of these instruments which reduces the temperature coefficient to a negligible quantity by using manganin instead of mercury. This instrument is equipped with a calibrated scale from which the resistance may be read accurately. Within reasonable limits the resistance is independent of the current.

Fig. 1 shows a sketch of the instrument. A copper and a manganin wire of the same diameter are welded together and slide on the inside of a thin glass tube $G_2$. This glass tube is surrounded by a thin copper tube $T$. All of this apparatus is inside of another glass tube $G_1$. The glass tubes are provided with reservoirs

[1] Published by permission of the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] F. Wenner, Phy. Rev. *32*, p. 614, 1911. This Bulletin Vol. 8, p. 584. Sci. Paper No. 181.

J. H. Dellinger, Phy. Rev. *33*, p. 215; 1911.

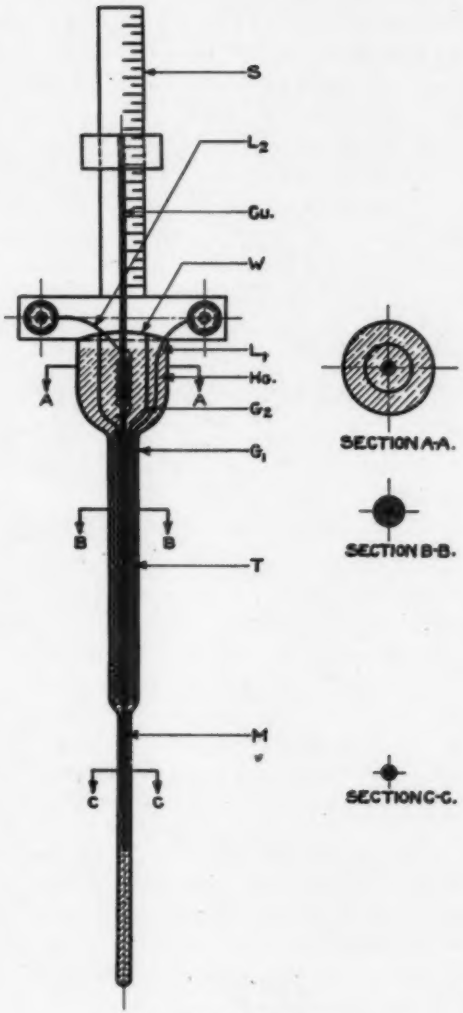


FIG. 1. Manganin Slide Resistor

through which the leads enter (Sec. AA). The entire system of tubes is filled with mercury. Thus the current flows in on lead $L_1$, down the copper tube $T$, through a thin film of mercury to the copper or manganin wire, and up to the inside reservoir, then through another thin film of mercury to $L_2$.

When the slide is down, the copper and manganin junction is at the lower end of the copper tube. If the slide is raised on the scale $S$, a portion of the manganin wire will replace an equal length of the copper wire. Thus resistance may be added continuously until the slide is at the top of the scale $S$, in which position the maximum resistance is obtained.

A resistor of this type having a range of one one-hundredth of an ohm has been used at the Bureau of Standards for about three years. The diameters of the wires are each about 0.260 cm. Their lengths are each approximately 15 cm.

The total inductance of the instrument is only about 0.023 microhenry. Since the copper and manganin wires each have the same diameter, there would be no change of inductance as the slide is moved were it not for the fact that the manganin, having a higher resistance than the copper, causes a little more current to flow through the thin film of surrounding mercury. The maximum change in inductance resulting from this change in current distribution is less than 0.001 microhenry.

The resistor has been calibrated a number of times during the last three years with currents of from 0.001 ampere to 5 amperes, and the calibrations are consistent to 0.0001 ohm. The calibration curve is a straight line, the calibrated points seldom being off the line more than a few hundred-thousandths of an ohm.

## SUMMARY

A continuously variable resistor which is suitable for carrying a large current and which permits the use of an accurately calibrated scale is described. The variation of the resistance is accomplished by substituting a manganin wire for a copper wire of the same length and diameter.

Readings may easily be repeated to one ten-thousandth of an ohm on a resistor having a range of .01 ohm and the instrument

remains constant to this degree of accuracy. The variation of inductance as the resistance is changed is negligible, being less than 0.001 microhenry for the total range of the resistor.

BUREAU OF STANDARDS
WASHINGTON, D. C.
JULY 25, 1922

# A ROTARY SLIDE-WIRE FOR PRODUCING UNIFORM VARIATION IN POTENTIAL DIFFERENCE[1]

BY
S. J. MAUCHLY

One of the requirements in the calibration of certain atmospheric-electric apparatus is a device for varying the potential difference between the two members of a condenser at a constant and definitely known rate.[2] A special form of "rotary potentiometer," which was devised for this purpose and constructed in the instrument-shop of the Department of Terrestrial Magnetism, is described here in the hope that it may be found applicable to other uses.

The description will be facilitated by a preliminary statement of the principal requirements to be satisfied. Briefly, these are as follows: (*a*) A slide-wire of sufficiently high resistivity and low thermal expansion to allow the use of the required terminal potential differences without objectionable expansion and other thermal effects. (*b*) A supporting cylinder which, in addition to satisfactory insulation, has approximately the same thermal expansion as the wire. (*c*) A traveling contactor which maintains good electrical contact; likewise, suitable brushes at the ends of the cylinder. (*d*) A driving mechanism for turning the cylinder uniformly at desired speeds. (*e*) Provisions for altering the speed of the cylinder. (*f*) Means for accurately determining the speed of rotation of the cylinder. (*g*) Convenient regulation of the potential difference applied to the slide-wire. (*h*) Such co-ordination of the various details that the rate of change in the potential difference between the traveling contactor and either terminal of

[1] Published by permission of the Director, Department of Terrestrial Magnetism.

[2] See, for example, "An Apparatus for Automatically Recording the Electrical Conductivity of the Air" by W. F. G. Swann, in "Annual Report of the Director of the Department of Terrestrial Magnetism" for the year 1917, Yearbook of the Carnegie Institution of Washington, 1917, p. 279. As indicated in the paper referred to, a preliminary form of the apparatus here described was used by Swann in 1917.

the slide-wire may be known and kept constant to about one part in 250 for observation periods of at least 5 minutes.

Fig. 1 shows a general view of the apparatus and its control equipment. (Only the upper half of the switchboard is involved

FIG. 1. General View of Constant-rate Slide-wire and Control Equipment

in the control of the slide-wire; the lower half is related to apparatus associated with the slide-wire for calibration and does not concern us here.) Fig. 2 is a schematic diagram of the slide-wire connections, exclusive of motor control, while the drawings reproduced in Fig. 3 give plan, and front and side elevations, drawn to scale, showing the more important details of construction. The

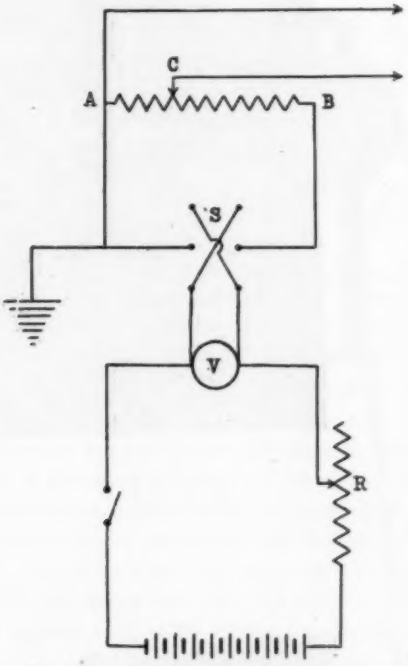


FIG. 2. Schematic Diagram of Slide-Wire Connections

photograph in Fig. 4 shows the apparatus as seen from above, with protecting cover removed, and gives certain mechanical details not shown elsewhere. As shown in Figs. 1 and 3, the present apparatus was constructed for wall mounting, but this is merely a detail of adaptation to surroundings. In what follows attention will be limited mainly to matters not brought out by the

figures, or which are of first importance for the proper functioning of the apparatus.

The slide-wire $AB$ of Fig. 2, consists of about 25 meters of No. 25 (B. and S. gauge) annealed chromel wire. This is wound under

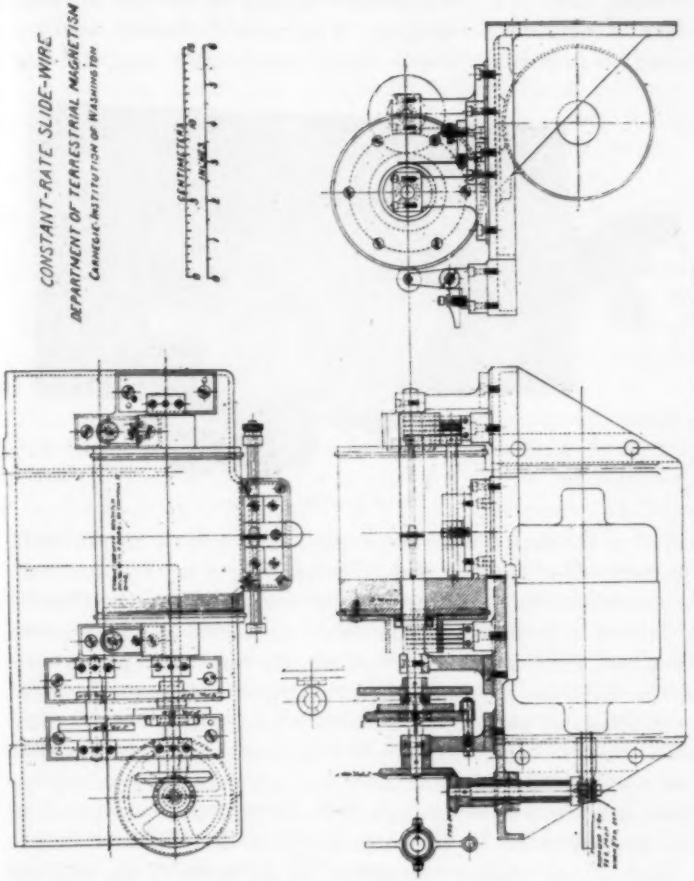


FIG. 3. Plan and Elevations, Constant-Rate-Slide-Wire

moderate tension, in a screw-cut spiral groove of 80 turns, on an accurately-turned white marble cylinder whose diameter and length are each approximately 10 cm. The spiral groove has a

pitch of about 1.25 mm (20 threads per inch) and is cut to a depth of 0.15 mm with a round nose tool of 0.225 mm radius. The resistance of the wire is about 150 ohms, and heating effects are negligible for applied voltages of the order of 30 volts. Even with 36 volts there is no perceptible loosening of the wire although there is noticeable warming. The marble cylinder was first bored to receive its shaft. After being rigidly mounted and

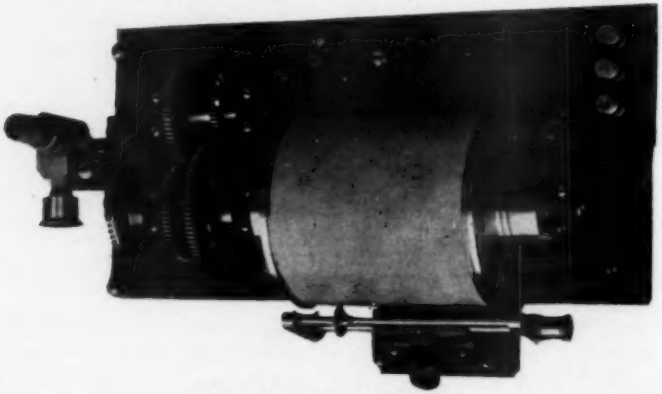

FIG. 4. View of Slide-Wire from Above

keyed to the shaft it was turned into final shape, on its own shaft, by means of a diamond tool. The cylinder is faced at each end by a combination face-plate and slip-ring, secured to the cylinder by screws tapped into the marble. As shown in Fig. 3 (front elevation) the clearances between the slip-rings and the lock-nuts of the shaft are such as to provide ample insulation. In order to eliminate all uncertainty as to the effective length of the slide-wire, the first two turns, at either end, are securely soldered at one point to the adjacent face-plate. Careful determinations, made after the wire was wound, show the resistance per turn to be practically uniform for the entire length of the cylinder.

Each of the brushes connecting the slip-rings to the binding-post terminals, consists of a single piece of phosphor bronze (No. 28, B. and S. gauge), slotted for the greater part of its length into five 3-millimeter strips. The brushes and binding posts are

mounted on hard rubber blocks of which the details are shown in Fig. 3.

The traveling contactor, represented by *C* in Fig. 2, consists of a brass wheel 15 mm. in diameter with a 60° V-shaped groove, about 0.2 mm deep, for engaging the wire. It is mounted on a steel axis which is parallel to the axis of the cylinder and along which it slides as it follows the wire spiral. The axis of the contactor forms part of a rigidly-hinged frame which is insulated from the base by a slab of hard rubber. Figs. 1 and 4 show the general construction of the contactor and its supporting frame. Firm contact with the wire is maintained by means of a stiff spring, and a simple thumb lever at the middle of the hinged frame, enables one to raise the contactor for shifting its position to any part of the cylinder. The location of the contact spring, under the thumb lever, is best shown in Fig. 3, side elevation. With moderate care to keep contact surfaces clean, both the contactor and brushes have given very satisfactory service.

The cylinder is operated by a 1/40 h.p. direct-current, shunt-wound motor with a normal speed of 1800 r.p.m. Suitable speeds for the cylinder are secured by means of a steel worm, attached to the motor shaft, and a double train of cut brass gears. The two reductions in speed thus obtained are 144 to 1 and 432 to 1, respectively, and are controlled by a shift-lever. Further changes of speed and all close adjustments are made by means of a rheostat in series with the armature. In the present form of the apparatus the time required for the contactor to travel the entire length of the slide-wire may be varied from 5 minutes to 25 minutes. The motor is energized by a storage battery in order to avoid the irregular fluctuations of commercial circuits. There is, however, the usual slow initial increase in speed so that the best conditions for constant speed are not reached until after the motor has been running for a time. This slow change of speed is, however, easily controlled by the rheostat and causes no trouble.

A tachometer of a type used for indicating speeds of air-plane propellers is attached to the motor shaft, as shown in Fig. 1. By this means the actual speed of the cylinder is readily determined

to one part in 300, or even better, and the sensitivity of the tachometer is such that, by aid of the control rheostat, the speed may also be kept constant to about one part in 300.

The rheostat indicated by $R$, in Fig. 2, is used for the control and adjustment of the over-all potential difference. With this in mind, one might be led to question the need of providing more than one speed for the operation of the cylinder, since the applied potential difference may be reduced at will. However, it is preferable to obtain the lower rates of change in potential difference by reducing the speed of the cylinder in order to keep the readings of the voltmeter well removed from the lower part of its range and to reduce the importance of contact effects. The use of the pole-changing switch $S$ (Fig. 2) is obvious from the diagram.

The apparatus described has been in use for nearly a year and has been found well adapted to the work for which it was designed. With the present form it is possible to secure variation in potential difference, uniform to 1 part in 250, for values ranging from several millivolts per second to about 0.1 volt per second, with the absolute values known to somewhat higher accuracy. This, naturally, does not indicate the limit of merit to be secured by this type of apparatus. With greater care in the selection of the resistor, special treatment of the marble, greater attention to contacts and motor control, both the constancy and the accuracy could be considerably increased if needed.

The author is under obligation to Mr. C. Huff for the design of many of the details and for the preparation of the drawings; the apparatus was constructed under his general supervision, in the instrument-shop of the Department, with the assistance of Mr. W. F. Steiner. Valuable assistance was also received from Mr. O. H. Gish in the determination of the attainable accuracy and degree of constancy.

DEPARTMENT OF TERRESTRIAL MAGNETISM
CARNEGIE INSTITUTION OF WASHINGTON
WASHINGTON, D. C.

# A SIMPLE DIRECT-READING POTENTIOMETER FOR STANDARD CELL COMPARISONS

BY
MARION EPPLEY AND WILLIAM R. GRAY

Of the many types of potentiometer that have been described[1] there are but two which are available for the direct comparison of the electromotive forces of standard cells. They are the "slide-wire" type, and the "Feussner" type.

The "slide-wire" type is the better of the two theoretically, on account of the absence of contact resistances in the measuring circuit. However, it possesses an uncertainty due to the inability of adjusting a slide-wire to uniformity of resistance over its entire length. Also, it is impracticable to manufacture an instrument of this design reading to more than five figures. In the range required for standard cell measurements, this makes the fifth decimal place an estimated one. This place can be estimated to about 20 microvolts upon high-grade instruments. Thus, their precision is approximately .002%, while their accuracy is usually guaranteed to .02% at their full scale reading.

The "Feussner" potentiometer is expensive to make owing to the great number of coils and the need of their being accurately adjusted to each other to insure a measuring current of constant value. The contacts also must be most carefully designed, made, and cared for, if the intended accuracy of the instrument is to be maintained. White[2] states that an error of ten microvolts or more may result from lack of care of the contacts in the Feussner potentiometer as made by Otto Wolff, a maker noted for his elaborate and smooth-working switches. The Feussner potentiometer could be made with an infinite number of dials in so far as theoretical

[1] White, J. Amer. Chem. Soc., *36*, p. 1868–1875; Laws, Electrical Measurements, p. 273–288; Watson, Practical Physics, p. 495–498; Griffiths, Methods of Measuring Temperature, p. 60–66.

[2] White, Ref. 1, p. 1871.

considerations are concerned. From the practical standpoint, six figures are all that can be secured owing to the total resistance being fixed at its upper limit by galvanometer sensitivity and insulation leakage, and at its lower limit by the resistance of the dial switches.

There are ways[3] in which the residual emf of two opposed standard cells can be measured to ten microvolts or better without any very great accuracy in the resistance and ammeter forming the set-up. Difference methods, however, do not give final results without calculation, an objection when a large number of routine measurements must be made.

If an accuracy of ten microvolts or better is desired, without the need of calculation, some such arrangement as that described below is necessary. In this design the two potential-point feature of the slide-wire type of potentiometer is retained with its advantage of absence of contact resistances in the measuring circuit. The uncertainty due to lack of uniformity in the slide-wire is eliminated by the use of coils throughout. The use of coils is made possible by limiting the range of the instrument to that required for comparing standard cells. No originality is claimed, except perhaps for the self-checking feature.

DESCRIPTION: The diagram gives all salient features of the potentiometer circuit. The reproduction of the photograph of the top shows the arrangement of dials and switches. The self-checking device is perhaps not so evident, for in adjusting the measuring current no coils are used other than those of the potentiometer circuit proper.

Each stud is drilled, on a radius greater than that of its switch-arm, with a hole reamed to receive a plug. A flexible connector with plug $S_1$ is attached through the standard cell to one pole of a double-throw switch. Another flexible cord with plug $S_2$ is attached directly to the other of this pair of poles. The opposite two poles of the double-throw switch and its two middle poles are connected as is usual in self-checking potentiometers. When the two plugs are inserted in the holes in the two studs corresponding to the

[3] Lindeck and Rothe, Zeitschr. f. Instrumentenkunde, *20*, p. 293, 1900.

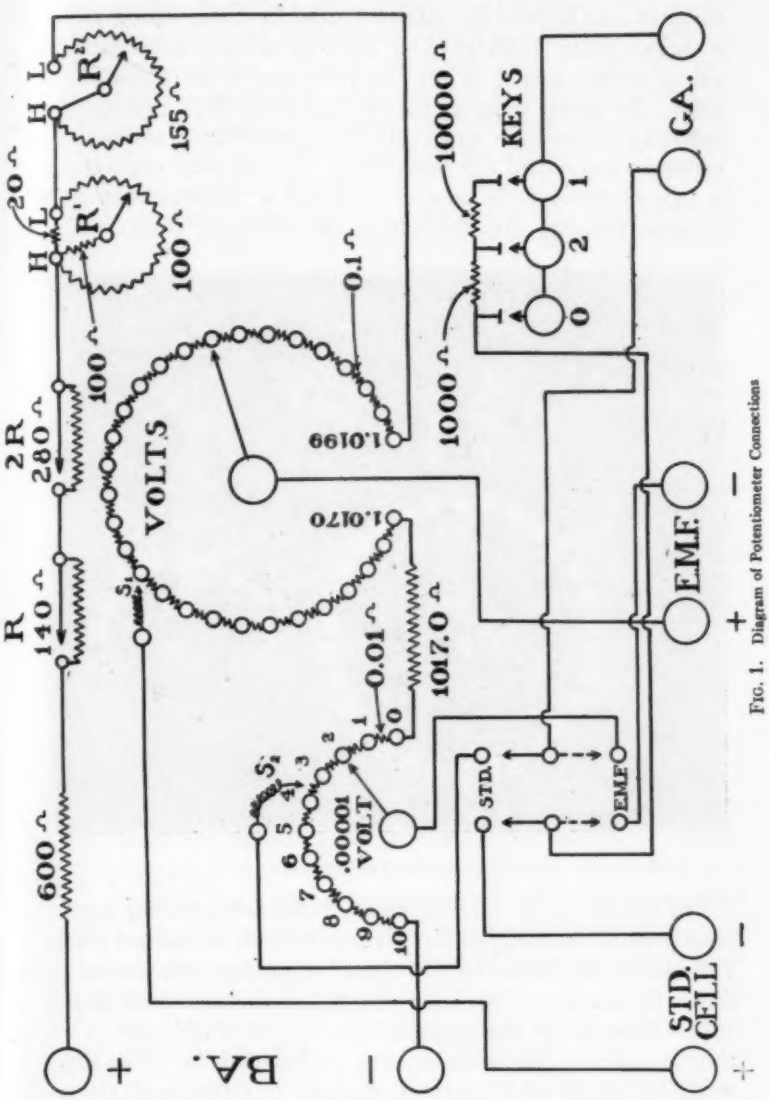


FIG. 1. Diagram of Potentiometer Connections

electromotive force of the standard, and the double-throw switch is thrown to the "Standard Cell" side, the cell is in series with the galvanometer, and is across the resistance proportional to its value. By simply throwing the switch to the E.M.F. position, the unknown is thrown in series with the galvanometer, without disturbing the standard cell connections. In this way, convenience is secured without the need of adjusting a "standard cell coil" to proportionality with the coils of the measuring circuit.

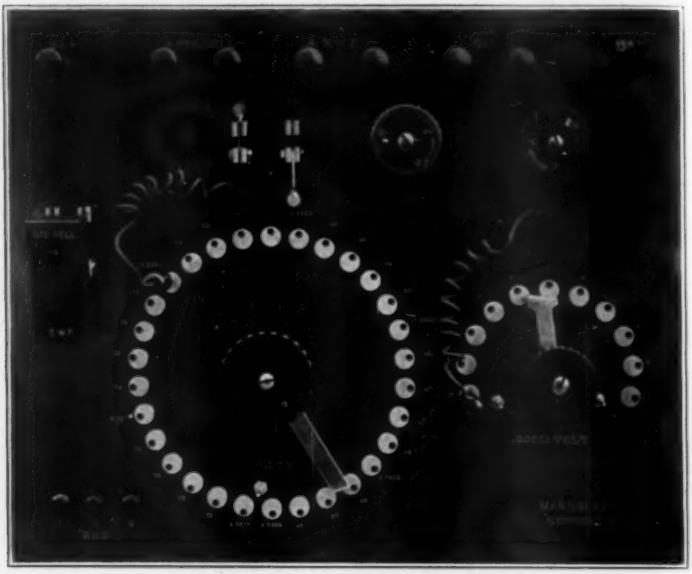

FIG. 2. Top of Potentiometer

The comparison of a cell having a value falling at the uppermost point of the range of the instrument, with a standard whose value lies at the lowest limit of the range, presents the worst condition for accuracy. An error of 0.1% in the resistance of the 1017.0 ohm coil of the potentiometer circuit would, under the above conditions, introduce an error of 3 microvolts. The same would be true of a 0.1% error in the same direction in all the resistances of the two dials, the 1017.0 ohm coil remaining constant.

To secure uniformity of temperature, the instrument is immersed to the bottom of the ebonite plate in a stirred oil-bath.

A highly sensitive galvanometer is necessary. Most excellent results have been secured with a Leeds & Northrup Company Type HR galvanometer having the following characteristics; sensitivity 2460 megohms; 2.03 mm per microvolt; 102 ohms resistance, 12 seconds period.

The parasitic electromotive force across the standard cell binding posts, with the battery disconnected, but the galvanometer connected as usual and the key O closed, was less than five microvolts, the checking switch being closed at the "Standard Cell" position. With the checking switch at the "E. M. F." position, the parasitics across the E. M. F. binding posts were about five microvolts. Swinging the long arm over its entire range of travel twenty times, as rapidly as possible, produced an E. M. F. of 18 microvolts which in thirty-five seconds sank to 5 microvolts. Swinging the short arm twenty times in the same manner produced an E. M. F. of 10 microvolts which sank to five microvolts in thirty seconds. Measurements were made with a Leeds & Northrup Company Type K potentiometer using the "low range."

A storage cell was found to drift too rapidly for satisfactory results. A standard battery was therefore made differing from that described by Hulett[4] in the following details: A crystallizing dish 17 cm in diameter and 9 cm deep was placed in the center of another crystallizing dish 25 cm in diameter and 12 cm deep. The inner dish was partially filled with mercury and mercurous sulfate. Into the annular space molten 12½% cadmium amalgam was poured to a depth of about 2 centimeters. Crystals of cadmium sulfate were placed in both dishes and both dishes filled with a saturated, acidified solution of cadmium sulfate. A cover was provided, and suitable connectors of platinum wire in glass tubing.

[4] Hulett-Phys. Rev., *27*, 33.

Two of these cells have proved sufficient.[5] After the lapse of two hours or more after adjustment of the measuring current, not more than a millimeter deflection of the galvanometer is customary if the current had been flowing for half an hour before the adjustment. When not in use, the circuit is kept open. Two such cells have been in use for 7 months and are still giving the same service as originally. They have received no attention.

Check-measurements on standard cells, made with this potentiometer, by the opposition method of Lindeck and Rothe,[6] and by the Bureau of Standards, usually agree to ten microvolts or better.

THE EPPLEY LABORATORY,
NEWPORT, R. I.

[5] Note: These two cells would not operate a Leeds & Northrup Company Type K potentiometer satisfactorily.

[6] See reference 3.

# ON CONSTRUCTION OF PLATINUM THERMOMETERS AND OF RESISTANCE COILS

BY
J. R. ROEBUCK

While zeros of platinum thermometers are generally much steadier than are those of mercury-in-glass thermometers, nevertheless the most serious difficulty in work of high precision is the zero shift. Such observed shifts may be due to many different causes. For example; (a) to shift of lead resistance with temperature or handling, (b) to shift of insulation resistance, (c) to shift of reference coils resistance, and (d) shift in resistance of the thermometer coil itself.

Causes (a) and (b) can be located with certainty and eliminated by well known methods. In this connection it might be emphasized that lamp cord is a very unsuitable material for such leads. But (c) and (d) are very difficult, indeed, to separate. In fact, what one observes always is the difference between shifts due to these two causes. Approximate separation of the shifts may be obtained by imposing temperature excursions on the thermometer, so that the time for which it is away from the reference temperature is short. This is limited to the detection of shifts in the thermometer due to temperature change. Secular shifts are also important and here the only means of separating and measuring is by reference to a non-varying resistance. The proportional variation involved in thermometer work, say for 0.001°C at room temperature, is of the order of 3 parts in a million which is probably beyond the limit of steadiness of the best standard resistances.

The causes of resistance shift of reference coil and of thermometer coil are necessarily very much alike. They may be summarized thus: (a) gradual relief from mechanical strain due to previous handling, (b) both imposition of and relief from strain during use, (c) changes in the composition of the resistance

material from the outside as oxidization of the surface of the resistance wire, or attack by acid in the bath liquid, or contamination of the platinum wire by silicon or metallic vapors, (d) changes in the internal character of the material due, for example, to crystal growth, or to concentration changes of solid solution and so on.

Cause (a) is usually met by annealing at a temperature well above that at which the coil is to be used. This may be made fully adequate for the Pt coil by heating electrically in air. For the resistance wires, usually manganin, this is difficult to do on account of oxidization of some components in the wire which not only changes the total resistance but also its temperature coefficient. It is undoubtedly one of the principal causes of resistance shifts in newer coils and may easily remain of very objectionable magnitude over the time for which such coils are used.

Cause (b) is one of the main reasons for shift of resistance of both coil and thermometer. Thus standard resistances are wound embedded in shellac, on a metallic cylinder. The coefficients of expansion of the wire, of the shellac, and of the cylinder are all different. The result of temperature change is to impose strains on all the parts and these may or may not remain entirely elastic. If any permanent deformation occurs anywhere, it will show itself by a shift in the resistance when the reference temperature is again attained. It is easily conceivable that the readjustment of the resistance to the reference temperature state might take time and the resistance therefore drift for hours or days.

Or consider the standard method of construction of platinum thermometers.[1] The wire is wound in notches on the edges of 4 mica strips, so that it makes a square. It is wound tight at room temperature. A rise in temperature allows the wire to become loose on its support, in annealing for instance, and on cooling it grips the points of support again. If it has shifted on the support any minute amount, the bends have to accommodate it, that is, the wire is being continually re-strained. Experimentally, it was found that a wire wound in a thread cut in a nonconductor was

[1] See Summary by T. S. Sligh, Bur. of Stand. Sci. Paper, No. 407.

even worse in its erratic zero shifts, which is to be explained in the same way.

These conditions require that for the platinum thermometer, the wire be supported in such a way as not to strain it either from handling or from temperature change. As the wire must be of very small diameter to give the required resistance the supporting points must be close together. On the other hand, the support must not be a constraint. Some experimental work which the writer has had under way for years required the measurement of small differences of temperature at not exceeding 300°C. The difficulties encountered led to much experimental work. The following procedure for the construction of a thermometer for this range is a summary of this phase of the work.

A spool of metal for carrying four strips of mica is constructed as in Fig. 1, which shows, also, cross sections at the important

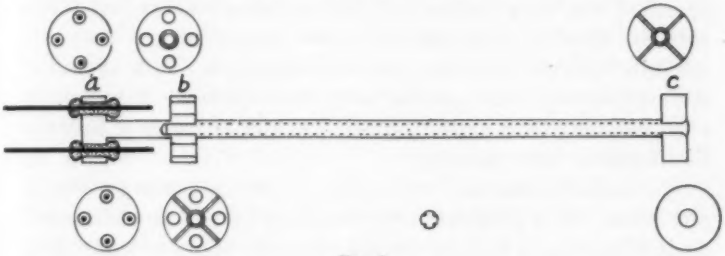


FIG. 1

places. The dimensions used are set by the space and resistance requirements. A cylinder of 3-4 cm long and 5 mm diameter can carry a meter of 0.05 mm platinum wire having about 50 ohms resistance at 0°C. The narrow and thin strips of mica are slipped into the radial slots of the spool bc, so that the outside edge of the mica is about flush with the cylinders. The strips need support over their length by the slots in the central rod. A light prick with a center punch beside the slot on the cylinders b and c will hold the mica in the slot during handling. The cylinders b and c have four holes, alternating with the slots, as indicated in the figure. Pieces of platinum wire about No. 20 and 2-3 cm long are covered with lead glass fused on to let it slip into the hole in "a" up

to a knob at one end. A little ring of the lead glass is slipped over the wire and fused on using a small pointed flame, with the result shown at "a." By crowding the soft glass close to the brass it is possible to leave very little play. Four such leads are each silver-soldered to a copper wire long enough to reach out of the thermometer case. These are then bound together while the coil itself is constructed. The four leads thus make a very substantial support for the spool carrying the thermometer coil with very little chance for straining the fine wire.

The spool bc with the mica strips in place is cast in wax, forming a cylinder out as far as the edges of the mica. Half beeswax—half resin is a suitable wax. This cylinder is turned down in the lathe till the surface is slightly below the ends of the spool. A double thread is cut in the wax and mica with a very pointed threading tool, the number of threads being determined by the length of wire to be carried and the diameter and length of the available spindle. It is possible to use 100 threads per inch successfully both in the cutting and subsequent use. It is, of course, not necessary that the space between the threads be cut to a sharp edge, but the groove must be sufficiently wide and deep to hold the thermometer wire securely.

The compensating lead connection of the fine platinum wire is put in first. It is led through the hole in cylinder b around a semicircumference and back to the diametrically opposite lead. It is insulated from the metal around the holes by a thin tube of glass either fused down on the wire for its length through the hole, or only at one end to prevent it slipping along the wire. Care must be taken that the wire has slack enough not to be broken by whatever looseness the leads may have. This is only important during the handling as when the coil is in the protecting tube, the leads will be unable to move materially. It is possible to proceed here to the silver soldering of the fine wire to the heavier platinum leads but it is difficult to avoid some fusion of the wax. It is safer to seal the wire in place by bringing near the wax a warm point, and proceed to wind the main coil. The two ends of the wire are insulated and held in place, as for the short wire. The spindle is mounted in the lathe and the wire stretched in a loop from the two

fastened ends by a piece of thread tied to the loop, passed over a round bar and loaded with a weight of a few grams. The wire is annealed at a dull red heat by a suitable electric current. The two wires are then wound in the double thread with care to assure that the wires go well down into the groove and that no small shavings of wax support it irregularly. The wire near the end of the loop is caught in place by a hot point held near the wax, and the loop is then fastened at leisure by a piece of the same platinum wire passed through a fine hole bored through one of the mica strips.

All four wires are then silver soldered to their respective leads with a fine pointed flame. The operation goes more readily if the leads have been prepared with a little silver solder on the end so it is only necessary to have the fine wire in contact with the fused silver to make the joint. A little silver solder may be readily transferred from another bit of platinum wire if necessary. The making of the four joints without fusing the wax seriously required some practice and care. The wax may be protected from fusing by holding the cylinder b in a vise and slipping a narrow piece of mica under the wire being heated. An oxy-gas flame may be made very small and yet give the required heat and hence does the best work. The making of these joints may be delayed till the wax is removed, but the coil is then very easily injured. The wax is removed by a suitable solvent, hot turpentine serves well for the half-and-half and the turpentine can be removed by a volatile solvent like carbon tetrachloride.

The annealing just before winding assures that the coil will do no springing on removal of the wax. If it be now annealed by passing an electric current, the coil squirms all out of place. This may be entirely avoided by warming the coil gradually inside a hard glass tube by heating the tube with one or more gas flames. While hot a small current will make the wire incandescent and complete the annealing.

This results in a perfectly cylindrical coil with the wires as exactly spaced as the thread was cut. The wires are well supported at four points without any unusual bend at the point of support. Any adjustment due to temperature changes can result only in long radius bends which will not exceed the elastic limit. Ex-

perience over several years with such coils shows that they have very steady zeros, the steadiest in fact of any arrangement yet tried here. Any numerical statement of the zero shift is of little value since it is complicated by the unknown variation of the reference coils and of course though probably to a smaller extent, by the variability of the ice bath temperature.

Conduction along the leads may be minimized by threading the wire through holes in short metal cylinders which fit the case and are separated from each other by nonconductors. The leads are insulated from the metal cylinders by thin glass tubes. In between the metal cylinders these are made of much thicker glass and so serve to space the metal cylinders. The result is to improve the radial conductivity without affecting the axial, so that at each point the leads will be kept near the temperature of the material surrounding the stem. The 4 platinum-copper junctions are arranged to come in the middle of the first or second metal cylinder. These four junctions are thus held together in temperature even during changing temperature. These junctions are the main location of thermals in the circuit, and this arrangement excludes them practically completely. In the set-up used by the writer for years there are no erratic motions of the light spot with a galvanometer sensibility of $10^{-9}$, and almost no zero shift. It should be added that the galvanometer circuit in the bridge is entirely copper (no brass binding posts) and is never opened: the bridge is operated by manipulating the applied potential and the slide wire contact is in the battery circuit.

The introduction of a metal spindle in the thermometer and of the metal about the leads, increases the heat capacity of the thermometer and therefore of the lag when measuring a changing temperature. Where the reduction of lag is of primary importance this type of construction may not be the best. In all cases the steadiness of the zeros is of primary importance for precise work and in many cases lag is quite secondary. It is these cases where this type of construction is particularly suitable.

It is evident that a similar type of construction should improve the steadiness of the resistance coils. The conditions are somewhat different, however. The coils can be made much larger and

longer before the size gives rise to difficulty. The manganin wire is very stiff and a very hard wax would be needed around which to bend the wire. The difficulty of preventing surface oxidization makes it desirable to use a much coarser wire. Coils were consequently built as follows.

Four grooves are milled out of a brass cylinder ½ inch diameter and 5 inches long to give it the cross section indicated in Fig. 2a. These four grooves are filled with paraffin wax by slipping this cylinder inside a brass tube, filling with melted paraffin and after

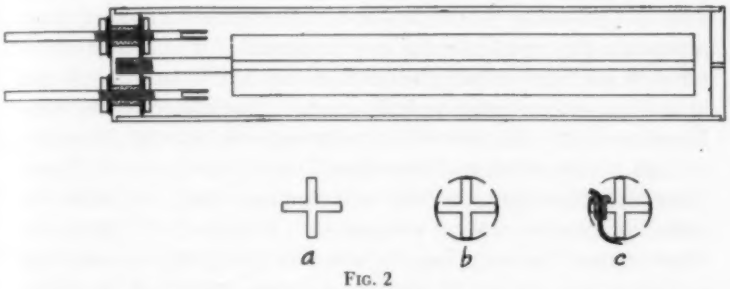


FIG. 2

thorough cooling slipping the tube off by heating it rapidly. Four strips of mica are laid along the cylinder as indicated in Fig. 2b. The edges of the strips do not meet so that the wire when wound on does not have a complete cylindrical support but may spring in and out in each quadrant as required by the temperature conditions.

The wire is doubled for non-inductive winding and a copper wire hard soldered to the bend. This may be done with very little heating of the resistance wire by holding both wires together end on in clamps. A gas flame fed with a little oxygen enables one to heat the joint very rapidly and transfer the liquid solder from another wire with the minimum heating of the resistance wire—when done successfully less than ¼ inch of the resistance wire may show the effects of heat. The copper wire is passed through a glass sleeve inserted in a hole in a wing of the supporting cylinder as indicated in Fig. 2c. A sharp bend in the copper wire is sufficient to hold it. The ends of the resis-

tance wire are fastened in a similar manner by hard soldering each end to two copper wires, one to serve for fastening and the other as current lead.

The mica strips are bound in place with a series of ties of string or wire. The winding of the resistance wire is begun at the doubled end and the ties removed successively as they are replaced by wire. The paraffin is then melted and washed out by suitable solvents.

There is no need for covering on the wire if it be carefully spaced in winding. Also there is nothing in the construction to prevent the coil being heated to 400-500°C. With suitable vacuum protection this should be the best treatment. The procedure so far used has been to heat the coil to about 135°C for many hours in air in a space heated by boiling xylol. The surface of the wire becomes slightly discolored at this temperature which is therefore as high a temperature as one should use in the presence of air. After this treatment the wire still remains very stiff and will spring uncoiled strongly if unfastened. This is a good reason for thinking that this annealing is a long way from adequate and that a considerable portion of unrelieved strain remains in the wire. The resistance changes show also that considerable strain has been removed.

After annealing the coil is dipped in a good grade of shellac dissolved in pure alcohol, so as to make a fairly thick varnish. It is dried by holding a few hours at near 100°C. This gives a comparatively thin coating of shellac, hardly sufficient to distort the wire materially. If the shellac penetrates between the wire and the mica it can produce scarcely any strain. Nor can the change of hygroscopic condition of the shellac produce material changes in the strain.

To minimize any effect of moisture as well as to protect the wire from mechanical injury it is best to enclose each coil in a container with acid-free dry kerosene as indicated in Fig. 2. The leads are insulated from the container by mica disks under the nuts and a glass sleeve in the holes. The whole joint is set in fused shellac which is also fused on over the outside finally. The stout copper leads have small holes bored into them axially at the coil

ends and the copper leads from the resistance wire are soft soldered in these holes using resin dissolved in pure alcohol as flux. The brass cylinder is slipped on and soft soldered together with an iron using resin. The kerosene is put in through a small hole in the bottom which is finally closed with a lump of solder. The stout copper leads can be used for supporting the coils.[2]

Experience with such coils shows them to be materially better in steadiness than the older form. But there still remains relative variation of such a size as to be distinctly objectionable. The actual variation may easily be greater and it is these latter which come into the thermometer work.

The order of variation reached by many workers gives a fundamental interval constant to a few parts per 100 000, so that for this factor the accuracy is almost certainly better than any other associated physical measurement. But when one desires to read a small temperature difference to 0.001° or 0.0001°C the erratic or continuous variation from day to day makes such data very uncertain. This has been the writer's personal experience. Improvement in the steadiness of the system would increase one's confidence in the data very materially.

In this connection further work on manganin is very necessary. The writer has made up many coils with variations of many conditions, e. g., with and without shellac on silk insulation, with and without metallic calcium as a drying agent, oxygen and acid absorbing agent in the kerosene; on metal cylinders, or with four points of support, or without any support. Having no steady comparison resistance it has not been possible to conclude anything about the actual variation. There was always relative variation of a magnitude much greater than the limit of measurement and great enough to be very undesirable in thermometric work.

About the only experimental attack would appear to be the careful study of groups of coils made up in different ways till some means was found for reducing greatly the relative variation within a group. Differential treatment of members of the group would

[2] See this JOURNAL, 6, p. 175, 1922.

then enable one to judge of the effect of the different conditions. For example, how quickly does a manganin coil attain a steady resistance after a change of temperature. The writer has followed the steady drift of resistance of an iron wire coil for more than 24 hours after its resistance was changed by raising the temperature about 30°C for a short time. The change was of the order of $10^{-4}$ and large enough to render the coil absolutely worthless for its proposed use as a thermometer.

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MAY, 1922

# THE DRAINAGE ERROR IN THE BINGHAM VISCOMETER[1]

BY
WINSLOW H. HERSCHEL

## 1. INTRODUCTION

For the accurate determination of absolute viscosity it is usual to employ instruments with glass capillaries, more or less modified from the original form of Ostwald. These instruments differ in the arrangement of the bulbs in which the liquid is measured, and in the manner of filling with a definite working volume. In the instruments of Ostwald, and of Traube[2] there is a drainage error due to the variation, with the viscosity, of the volume discharged from the bulb. This error is avoided in the apparatus of Lidstone[3] by the use of mercury which does not wet the bulb, while in the Ubbelohde form of instrument the flow is into a dry bulb, and the measured volume is independent of the viscosity of the liquid tested.

The Bingham viscometer[4] shown in Fig. 1, is similar to the Ubbelohde in having two bulbs so arranged as nearly to eliminate the effect of variations in the density of the liquid, and in the use of a constant air pressure to cause the flow. The working volume is contained between the mark H and the overflow into the trap at A. When the temperature is raised, the volume is again adjusted by causing the surplus to run into the trap.

The volume of flow is contained in the bulb C, between the marks B and D. This bulb is alternately emptied and filled, if check tests are run, but it should be noted that from the method

[1] Published by Permission of the Director, U. S. Bureau of Standards.

[2] Holde-Mueller, Examination of Hydrocarbon Oils, p. *117*; 1915.

[3] F. M. Lidstone, Jour. Soc. Chem. Ind., *36*, p. 270, 317; 1917.

[4] E. C. Bingham and R. E. Jackson, B. S. Scientific Paper No. 298, p. 64; 1917. E. C. Bingham, Proc. A.S.T.M., *18*, part 2, p. 373; 1918. The word viscometer is used by Bingham and will be used throughout this paper to avoid confusion, even for instruments usually called viscosimeters.

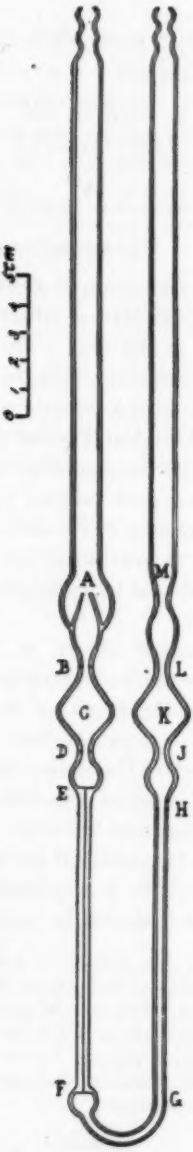


FIG. 1. The Bingham viscometer

of adjusting the working volume, the bulb is already wet before the first run can be made, so that a comparison can not be made between the capacity of the bulb to deliver, and of a dry bulb to receive.

Since the Bingham viscometer is used only where great accuracy is required, and since it is claimed that it is "accurate to a tenth of one per cent,"[5] an error which might be of no importance in another type of instrument can not be considered as negligible. It is evident that the drainage error will increase with the viscosity, or with the amount of liquid which clings to the walls of the bulb, and the error might be considerable when the instrument is used for testing lubricating oils, with viscosities up to 20 poises and over. Thorpe and Rodger[6] who used a similar instrument, concluded that for the comparatively fluid liquids with which they had to deal, with a maximum viscosity of 0.14 poise, a cylindrical form of the bulbs was preferable, in order that the contained liquid might the more readily acquire the temperature of the bath, although with spherical bulbs, as used by Ubbelohde, less liquid adheres to the walls. In the Thorpe and Rodger instrument there is a trap on both sides and each bulb is graduated, so that the working volume may be adjusted after the first run to allow for possible evaporation.

Barr[7] used an Ostwald viscometer for testing glycerin, with a viscosity of 1.26 poise, and remarks,

> The viscometer was filled by a pipette, the time of drainage of the pipette necessary for the accuracy sought being determined by experiment.

He does not appear to have considered whether the time of flow of his viscometer was sufficient or not to eliminate drainage error.

The object of this paper is to consider evidence of drainage error in the Bingham viscometer, and to estimate the magnitude of this error, or the time of flow necessary to render it negligible, with a bulb of 4 cubic centimeters capacity. While Bingham

[5] Proc. A. S. T. M., loc. cit. The effect of the uncertainty in regard to end effects, upon the demonstrable accuracy of the instrument, is considered in the discussion of this paper.

[6] T. E. Thorpe and J. W. Rodger, Phil. Trans. R. S., *185*, part 2, p. 423; 1894.

[7] Guy Barr, Reports and Memoranda, No. 755; Aeronautical Research Com., p. 4; London; 1921.

apparently paid most attention to correctness of average pressure and of working volume, he recognized[8] the danger of imperfect drainage, for he says:

Our theoretical investigation proves therefore that the bulbs of the viscometer should be as short as convenient, but with a large radius. The constricted portions should be both narrow and short. These objects may be best achieved without sacrificing good drainage, by having each bulb like two filtering funnels placed with their ends together.

## 2. CALIBRATION OF THE BINGHAM VISCOMETER

In the Bingham viscometer flow is caused by air pressure applied first to one side and then to the other when a check determination is desired. In an ideal instrument the time of flow would be the same in each direction, and there would be no hydrostatic head correction, but this is rarely attained in practice.

The calibration of the instrument has been fully described in B. S. Scientific Paper No. 298, to which the reader is referred for further details than can be given here. The usual assumptions are made that there is no turbulence and that the capillary is very long in proportion to its diameter. Then the coefficient of the kinetic energy correction is equal to

$$C' = \frac{1.12\,Q}{8\,\pi\,l} \tag{1}$$

where Q is the volume of the bulb in cubic centimeters, and $l$ is the length of capillary in centimeters.

In the equation

$$h' = \frac{\mu}{2\,C\,\gamma}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) + \frac{C'}{2\,C}\left(\frac{1}{t_1^2} - \frac{1}{t_2^2}\right) \tag{2}$$

h′ is a constant of the instrument used in correcting for hydrostatic head. $t_1$ and $t_2$ are the times of flow in the two directions, and could only be equal if the bulbs were absolutely alike. $\mu$ is the viscosity in poises, and $\gamma$ is the density in grams per cubic centimeter of the calibrating liquid.

Before using equation (2) it is necessary to calculate an approximate value of $C$ from the equation

$$C = \frac{\mu + \dfrac{C'\,\gamma}{t}}{pt} \tag{3}$$

[8] E. C. Bingham, H. I. Schlesinger and A. B. Coleman, Jour. Am. Chem. Soc., *38*, p. 32; 1916.

where $p$ is the pressure causing flow, in grams per square centimeter. For this purpose only, $p$ may be taken equal to $h$ = average manometer reading reduced to grams per square centimeter, or centimeters of water column, and then, after $h'$ has been obtained, $p$ and $C$ may be corrected and $h'$ recalculated if necessary.

The absolute viscosity in poises, is calculated from equation (3) in the form

$$\mu = C\ p\ t - C'\ \gamma\ /t$$

where $p$ is the corrected manometric pressure, and is equal to

$$p = h \pm h'\ \gamma - K \pm L \qquad (5)$$

where $h'$ has the plus sign when $t$ has the lower value, and the minus sign when the flow is in the opposite direction and $t$ is greater. $K$ is a correction due to change in density of water with the temperature and to weight of air in the manometer, and its value depends upon the manometric head and the room temperature, while $L$ is a minor correction due to difference in elevation of the center of the manometer and of the viscometer. Tables for $K$ and $L$ are given in *Scientific Paper* No. 298.[9]

For the instrument used in this work, $C'$ was calculated to be 0.01229 by equation (1) with the approximate values, $Q = 4$cc and $l = 14.5$ cm. The diameter of capillary was approximately 0.07 cm. The two other instrumental constants, $C$ and $h'$, were found as shown in Table 1.

The capillary was almost too large to calibrate with water, so that it was necessary to use very low manometric pressures. In some cases the manometer reading of only 11 centimeters was not large in comparison with $h'$ whereas Bingham[10] implies that for the most accurate work the manometer reading should be at least 30 $h'$. The value of .00000898 was obtained for $C$ four times out of the fifteen tests, and as it agrees fairly well with the average, it was taken as the most probable value. In calculating Table 1, $p$ was found and $C$ calculated separately for each direction of flow, and the values given are the averages of the two values thus obtained.

[9] For similar tables for use with a mercury manometer, see paper by E. C. Bingham and Henry Green, Proc. Am. Soc. Test. Mat., *19*, II, p. 651; 1919.

[10] Bingham, Schlesinger and Coleman, loc. cit., p. 32.

TABLE 1. *Calibration of Bingham viscometer*

| Calibrating liquid | Temperature | C x $10^8$ | $h'$ |
|---|---|---|---|
| | °C | | |
| Distilled water | 5 | 886 | .95 |
| Distilled water | 5 | 920 | .88 |
| Distilled water | 10 | 889 | .93 |
| Distilled water | 10 | 919 | .87 |
| Distilled water | 15 | 898 | .94 |
| Distilled water | 20 | 899 | .93 |
| Distilled water | 25 | 898 | .94 |
| Distilled water | 25 | 898 | .83 |
| Distilled water | 25 | 909 | .87 |
| Distilled water | 25 | 904 | .87 |
| 40% sucrose solution | 25 | 913 | .85 |
| 60% sucrose solution | 20 | 868 | .86 |
| 60% sucrose solution | 25 | 896 | .87 |
| 60% sucrose solution | 30 | 898 | .85 |
| 60% sucrose solution | 30 | 901 | .88 |
| Average | | 900 | .89 |

### 3. USE OF THE BINGHAM VISCOMETER

After $h'$ has been determined, it is not necessary to refer again to equation (2), but $p$ has to be determined for every test, by equation (5), since it varies slightly with the room temperature even if the manometer reading is not changed. The viscosity is then determined from equation (4).

A series of blends were made for use in calibrating technical viscometers, and their viscosities are shown in Table 2.

TABLE 2. *Viscosities of calibrating liquids*

| Sample No. | Temperature °C | Density g/cc | Viscosity Poises |
|---|---|---|---|
| 1 | 20 | .854 | .1847 |
| | 40 | .840 | .0873 |
| | 55 | .830 | .0559 |
| 2 | 20 | .894 | .3927 |
| | 40 | .881 | .1573 |
| | 55 | .871 | .0928 |

TABLE 2 (continued)

| Sample No. | Temperature °C | Density g/cc | Viscosity Poises |
|---|---|---|---|
| 3 | 20 | .884 | .4702 |
| | 40 | .871 | .1854 |
| | 55 | .861 | .1072 |
| 4 | 20 | .874 | .603 |
| | 40 | .860 | .2315 |
| | 55 | .850 | .1313 |
| 5 | 20 | .909 | 1.680 |
| | 35 | .899 | .664 |
| | 40 | .896 | .511 |
| | 50 | .889 | .320 |
| | 55 | .886 | .2592 |
| 6 | 20 | .875 | .872 |
| | 40 | .861 | .3198 |
| | 55 | .851 | .1787 |
| 7 | 10 | .970 | 25.06* |
| | 15 | .967 | 15.89* |
| | 20 | .963 | 10.21* |
| | 23 | .961 | 8.00* |
| | 25 | .960 | 6.84 |
| | 30 | .956 | 4.795 |
| | 35 | .953 | 3.312 |
| | 40 | .950 | 2.338 |
| 8 | 20 | .875 | 1.232 |
| | 40 | .861 | .440 |
| | 55 | .851 | .2395 |
| 9 | 20 | .819 | .02878 |
| | 40 | .805 | .01860 |
| | 55 | .794 | .01571 |
| 10 | 20 | .849 | .1232 |
| | 40 | .835 | .0620 |
| | 55 | .825 | .04147 |
| 11 | 20 | .859 | .2307 |
| | 40 | .845 | .1023 |
| | 55 | .835 | .0638 |

TABLE 2 (continued)

| Sample No. | Temperature °C | Density g/cc | Viscosity Poises |
|---|---|---|---|
| 12 | 20 | .882 | .531 |
| | 40 | .869 | .1851 |
| | 55 | .859 | .1064 |
| 13 | 20 | .876 | .714 |
| | 40 | .856 | .2638 |
| | 55 | .846 | .1466 |
| 14 | 20 | .872 | 1.038 |
| | 40 | .858 | .3691 |
| | 55 | .848 | .2009 |
| | 90 | .832 | .0690 |
| 15 | 20 | .887 | 1.563 |
| | 40 | .874 | .4491 |
| | 55 | .864 | .2211 |
| 16 | 20 | .901 | 1.333 |
| | 40 | .888 | .4175 |
| | 55 | .878 | .2141 |
| 17 | 20 | .873 | 1.266 |
| | 40 | .859 | .4435 |
| | 55 | .849 | .2387 |
| 18 | 20 | .911 | 1.686 |
| | 40 | .898 | .634 |
| | 55 | .888 | .3557 |
| 19 | 20 | .911 | 2.361 |
| | 40 | .898 | .829 |
| | 55 | .888 | .445 |
| | 90 | .870 | .1611 |
| 20 | 20 | .882 | 1.429 |
| | 40 | .869 | .502 |
| | 55 | .859 | .2701 |
| 21 | 20 | .926 | 2.599 |
| | 40 | .913 | .935 |
| | 55 | .903 | .514 |

TABLE 2 (continued)

| Sample No. | Temperature ° C | Density g/cc | Viscosity Poises |
|---|---|---|---|
| 22 | 20 | .892 | 3.20 |
| | 40 | .879 | .951 |
| | 55 | .869 | .4856 |
| 23 | 40 | .873 | 1.325 |
| | 55 | .863 | .639 |
| 24 | 40 | .873 | 1.446 |
| | 55 | .863 | .692 |
| 25 | 40 | .873 | 1.546 |
| | 55 | .863 | .728 |
| | 90 | .842 | .1982 |
| 26 | 40 | .878 | 2.250 |
| | 55 | .868 | 1.014 |
| 27 | 40 | .881 | 3.221 |
| | 55 | .871 | 1.415 |
| | 90 | .848 | .3360 |
| 28 | 20 | .930 | 6.725 |
| | 25 | .927 | 4.215 |
| | 30 | .923 | 2.764 |
| | 37.8 | .918 | 1.508 |
| | 45 | .914 | .933 |
| | 50 | .910 | .712 |
| | 54.4 | .907 | .554 |
| | 60 | .904 | .4143 |
| | 70 | .897 | .2714 |
| | 80 | .890 | .1790 |
| | 90 | .884 | .1236 |

Sample No. 5 is a French oil used in standardizing the Barbey viscometer. Sample No. 7 is castor oil, the viscosities marked with an asterisk having been estimated by comparison with another sample. No. 28 is the U oil referred to by Bingham.[11] A blown vegetable oil was used in mixing some of the more viscous samples, and the change of viscosity with the temperature is thereby decreased.

[11] E. C. Bingham, Bureau of Standards, Tech. Paper No. 204, p. 58; 1922.

## 4. THE SCOTT VISCOMETER

In previous work of calibrating viscometers[12] use was made of water and ethyl alcohol solutions which are not suitable for instruments with outlet tubes of large diameter, such as are used for determining the viscosity of varnishes or fuel oils. The Scott viscometer was the first of these large tube instruments to be calibrated with liquids whose viscosity had been determined by the Bingham viscometer, and a difficulty experienced in the calibration was ascribed to the drainage error of the Bingham instrument.

The Scott viscometer[13] is not essentially different from other technical efflux instruments, such as the Saybolt, Engler, and Redwood.

Table 3 gives dimensions of the Scott viscometer, according to the designer, and also gives dimensions of two particular instruments, one as measured by the Bureau of Standards, and the other as reported by the Ordnance Department.

TABLE 3. *Dimensions of Scott viscometers*

| Dimension | B. S. | Ord. Dept. | Scott | |
|---|---|---|---|---|
| | Cm. | cm. | inch | cm. |
| Diameter of oil container, at top | ..... | 8.66 | ..... | ..... |
| Av. diameter of oil container | 8.738 | 8.74 | 3½ | 8.90 |
| Diameter of outlet tube | .275 | .267 | .108 | .274 |
| Diam. of conical valve seat, at top | .956 | .864 | ..... | ..... |
| Length of outlet tube and lower conical flare | .628 | .686 | ⅜ | .953 |
| Length of lower conical flare | .05 | ..... | ..... | ..... |
| Length along axis of conical valve seat | .567 | ..... | ..... | ..... |
| Depth of upper end of conical valve seat below surface of water with 200 cc of water in container | 3.47 | ..... | ..... | ..... |
| Mean diam. of widest part of flare at lower end of outlet tube | .385 | ..... | ..... | ..... |

[12] Bureau of Standards, Tech. Papers Nos. 100, 112, and 125.

[13] Proc. Am. Soc. Test. Mat., Vol. 10, p. 117–146, 1910: A. H. Gill, Oil Analysis, p. 164; 1913: Wm. M. Davis, Friction and Lubrication, p. 42; 1904: W. G. Scott, Drugs, Oils and Paints, Vol. 13, p. 50; 1897–8.

According to Scott the outlet tube must be made by using a new No. 35 twist drill, and the time of discharge for 50 cc of water at 60°F (15°.6C) is between 10 and 11 seconds.

There is no filling mark so 200 cc of the liquid to be tested is measured in a graduated cylinder and poured into the container, the cylinder being left 10 or 15 minutes to drain if necessary. The data of table 4 were obtained with oils selected from table 2.

Fig. 2 shows a Higgins diagram[14] calculated from data of Table 4. The graph represents the equation

$$\text{kinematic viscosity} = \frac{\mu}{\gamma} = 0.0178\, t - \frac{2.74}{t} \qquad (6)$$

but since the outlet tube has a flare at both ends, it is not to be

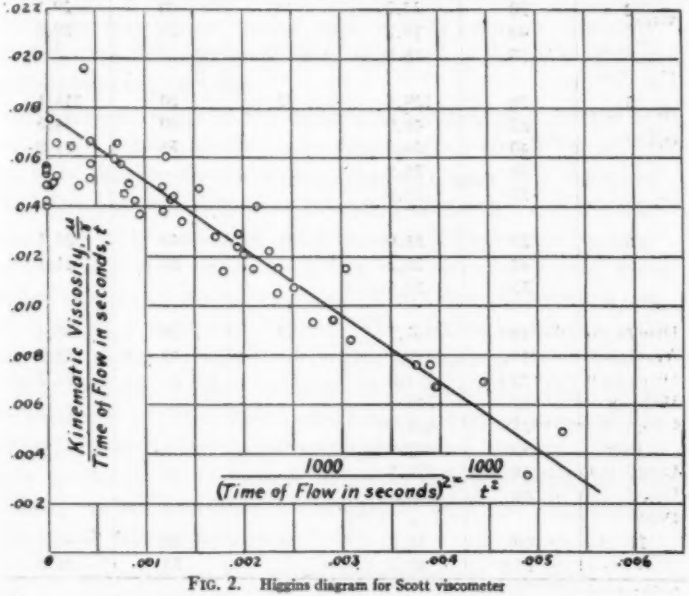


FIG. 2. Higgins diagram for Scott viscometer

expected that two instruments will have exactly the same time of flow or that equation (6) would be of general application. On account of the impossibility of accurately estimating the average

[14] W. F. Higgins, Jour. Soc. Chem. Ind., 32, p. 568, 1913.

diameter of outlet tube, no attempt was made to check equation (6) by a Herschel diagram similar to Fig. 5.

TABLE 4. *Tests of Scott viscometer, B. S. 6452*

| Sample No. | Temperature | Time | Sample | Temperature | Time |
|---|---|---|---|---|---|
| | ° C | Seconds | ° C | | Seconds |
| water | 15.6 | 11.2 | 12 | 40 | 19.9 |
| | | | | 55 | 16.3 |
| 1 | 20 | 20.6 | 13 | 40 | 24.1 |
| | 40 | 15.0 | | 55 | 18.5 |
| | 55 | 13.8 | | | |
| 2 | 20 | 32.2 | 14 | 40 | 29.1 |
| | 40 | 19.2 | | 55 | 20.6 |
| | 55 | 15.9 | | | |
| 5 | 20 | 129.8 | 15 | 20 | 118.1 |
| | 35 | 46.9 | | 40 | 34.5 |
| | 40 | 36.3 | | 55 | 21.0 |
| | 50 | 26.9 | | | |
| | 55 | 22.6 | | | |
| 6 | 20 | 51.0 | 16 | 40 | 23.1 |
| | 40 | 25.2 | | 55 | 21.3 |
| | 55 | 18.4 | | | |
| 7 | 10 | 1865.7 | 17 | 20 | 95.4 |
| | 15 | 1139.7 | | 40 | 35.5 |
| | 20 | 707.8 | | 55 | 22.7 |
| | 23 | 546.3 | | | |
| | 25 | 464.8 | | | |
| | 30 | 320.9 | | | |
| | 35 | 227.5 | | | |
| | 40 | 166.3 | | | |
| 11 | 40 | 16.0 | 18 | 40 | 46.8 |
| | 55 | 14.3 | | 55 | 28.0 |

It will be noted that very viscous oils, giving points at the extreme left of Fig. 2, show too low a value of the ordinate $\frac{\mu}{\gamma t}$. As there was a possibility that this was due to some peculiarity of the laws of flow through so short a tube of variable diameter,

it seemed that this should not be accepted as an indication of drainage error in the Bingham instrument without confirmation.

### 5. OTHER POSSIBLE CAUSES OF THE LOW VALUES OF $\frac{\mu}{\gamma t}$

Various possible causes for the low values of the ordinates of Fig. 2, at very high viscosities, seemed worthy of consideration. The error could not be due to the contraction of the oil after leaving the outlet tube of the Scott viscometer, because the error is most marked when tests are run at temperatures lower than room temperature. A drainage error in the Scott viscometer would lower the average head, increase t and thus decrease the ordinate, but it seemed unlikely that the error would be appreciable in an instrument having such a large, shallow container. The tests for drainage error were therefore made on a Saybolt Universal viscometer tube.

After making a run in the usual way, vacuum was quickly applied to the bottom of the outlet tube to draw out all the oil except that clinging to the walls. The maximum film thickness, calculated from the difference in weight of the dry and wet container, was 0.011 centimeter, with an oil of 5000 seconds viscosity. Further tests were made by filling the container to the level reached at the end of a normal run, 8.8 cm below the overflow rim, and applying a vacuum as before. The results showed that only 8 per cent of the oil which adhered to the walls in the first series of tests, was above the 8.8 centimeter level, so that the average film thickness on the walls exposed during a normal run would be only 0.0009 centimeter. Although this value does not strictly apply to the Scott viscometer, it seems safe to regard the film thickness as inappreciable in comparison with the 9 centimeter diameter of this instrument.

### 6. INDICATIONS OF DRAINAGE ERROR OF BINGHAM INSTRUMENT BY COMPARISON WITH SAYBOLT AND REDWOOD VISCOMETERS

Figs. 3 and 4 show calibration diagrams for Saybolt Universal viscometer No. 109. Fig. 3, like Fig. 2, shows too low an ordinate at high viscosities, while in Fig. 4 values of the abscissas near the

bottom of the graph are too large. Figs. 5 to 7 show Higgins diagrams for the Redwood No. 1, Redwood Admiralty, and Saybolt Furol viscometers, respectively. It will be noted that they all show the same signs of drainage error in the Bingham instrument, or some cause producing the same effect, so that it may be concluded that the evidence noted in Fig. 2 is not due to any peculiarity of the Scott viscometer.

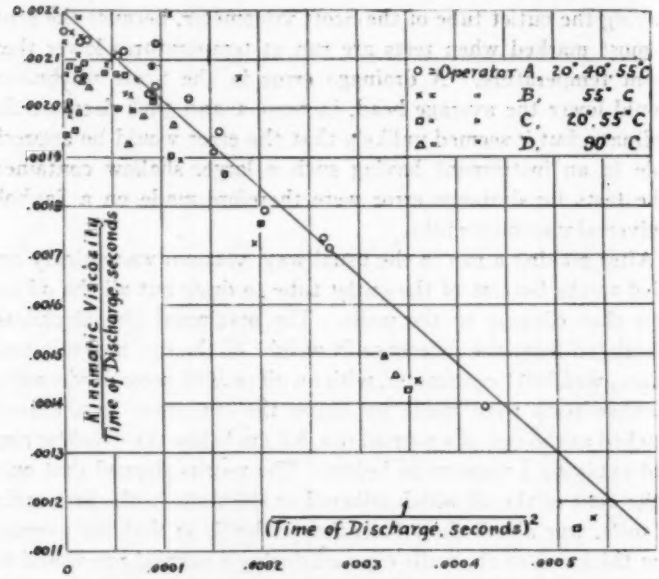


FIG. 3. Higgins diagram for Saybolt Universal viscometer No. 109

Fig. 8 shows another method of indicating the drainage error and was suggested by a diagram of Higgins.[15] The upper graph, from the work of Higgins, shows the relation between the time of flow of the Redwood viscometer and the kinematic viscosities obtained with a viscometer similar to that used by Thorpe and Rodger. The lower graph shows results obtained in calibrating

[15] W. F. Higgins, Collected Researches, National Physical Laboratory, *11*, p. 12: 1914.

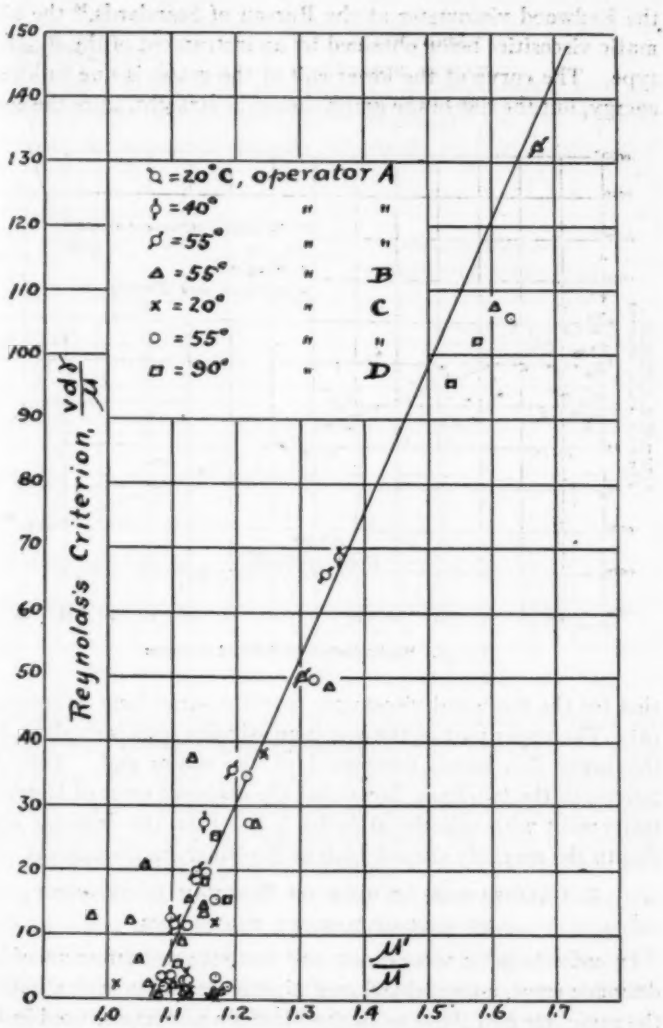


FIG. 4. Herschel diagram for Saybolt Universal viscometer No. 109

the Redwood viscometer at the Bureau of Standards,[16] the kinematic viscosities being obtained by an instrument of the Bingham type. The curve at the lower end of the graph is due to kinetic energy, but the rest of the graph should be straight, since the equa-

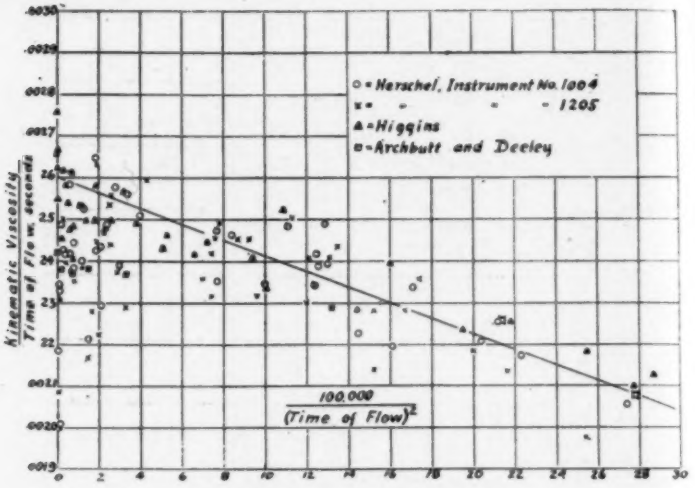


FIG. 5. Higgins diagram for Redwood viscometer

tion for the Redwood viscometer is of the same form as equation (6). The upper part of the line from Higgins tests is straight, but the lower line bends downward at the upper end. This difference in the two lines shows that the drainage error of Higgins's instrument with cylindrical bulbs, is less than the drainage error due to the specially shaped bulb in the Bingham instrument.

### 7. CALIBRATION OF BULB OF BINGHAM INSTRUMENT BY OILS OF VARIOUS VISCOSITIES

In order to get a more direct and accurate measurement of the drainage error, a special jacketed pipette was built with a bulb of the same size and shape as in the Bingham viscometer used in the work above recorded. There was no capillary and the rate of dis-

[16] Winslow H. Herschel, B. S. Technologic Paper No. 210; 1922.

charge could be regulated by a stop cock. The volume discharged could be readily determined from the density of the oil and the weight discharged.

Since the viscosity, by equation (4), is proportional to C, or inversely proportional to the volume discharged, the true viscosity will be to the apparent viscosity (as calculated from a value of C

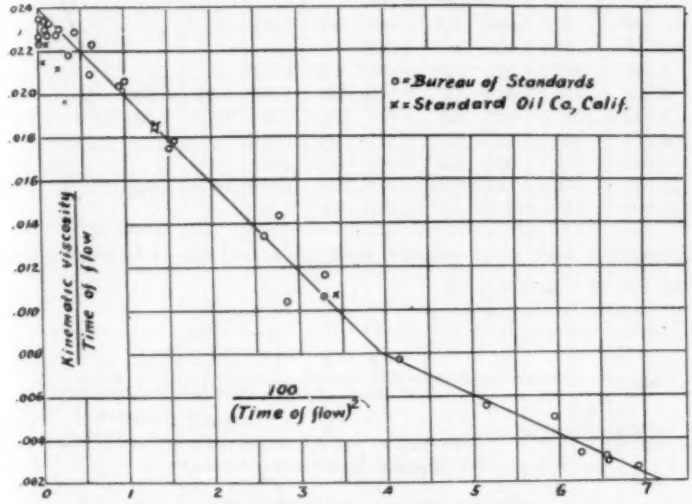


FIG. 6. Higgins diagram for Redwood viscometer, Admiralty type

determined by calibration with water) as the volume of water discharged from the bulb is to the volume of oil. The capacity of the bulb when calibrated with water was 4.232 cubic centimeters.

Table 5 gives results of calibration of the bulb with oils of various viscosities, the correction factor being the ratio of capacity of the bulb to discharge water and oil.

Fig. 9, from data of table 5, may be used in estimating the drainage error in a given test, or in selecting a time of flow so that the error will be negligible. The numbers on points indicate the correction factors, and lines of equal factors have been drawn. Data has been added from the work of Bingham and Young[17]

[17] E. C. Bingham and H. L. Young, paper presented before the Birmingham, Ala., meeting, A. C. S.; April, 1922.

TABLE 5. *Factors to correct for drainage error of Bingham viscometer*

| Corrected viscosity | Time | Factor | Time | Factor | Time | Factor | Time | Factor | Time | Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| Poises | Sec. | | Sec. | | Sec. | | Sec. | | Sec. | |
| .1278 | 463 | 1.000 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| .242 | 58 | 1.003 | 255 | 1.000 | ..... | ..... | ..... | ..... | ..... | ..... |
| .430 | 80 | 1.005 | 312 | 1.001 | 900 | 1.000 | ..... | ..... | ..... | ..... |
| .722 | 87 | 1.007 | 400 | 1.000 | ..... | ..... | ..... | ..... | ..... | ..... |
| 1.247 | 103 | 1.012 | 240 | 1.007 | 420 | 1.000 | ..... | ..... | ..... | ..... |
| 2.140 | 150 | 1.015 | 212 | 1.010 | 585 | 1.007 | 1524 | 1.003 | ..... | ..... |
| 3.642 | 296 | 1.012 | 600 | 1.011 | 1280 | 1.007 | 1070 | 1.009 | 2332 | 1.005 |
| 6.473 | 300 | 1.013 | 420 | 1.012 | 1181 | 1.007 | ..... | ..... | ..... | ..... |
| 9.560 | 343 | 1.018 | 846 | 1.010 | 1491 | 1.008 | ..... | ..... | ..... | ..... |
| 12.160 | 744 | 1.015 | 1168 | 1.011 | 1680 | 1.010 | 2862 | 1.006 | ..... | ..... |
| 17.960 | 728 | 1.019 | 1351 | 1.012 | 2700 | 1.010 | ..... | ..... | ..... | ..... |

showing a somewhat smaller drainage error, due it is believed to the use of a larger bulb.

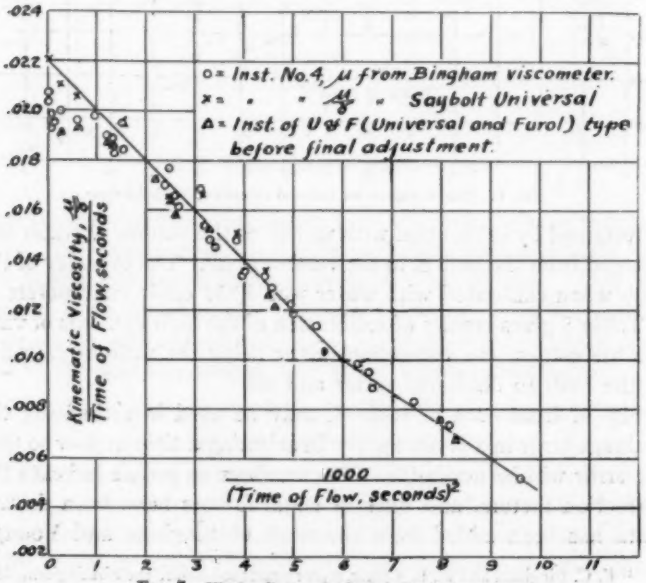


FIG. 7. Higgins diagram for Saybolt Furol viscometer

## 8. METHODS OF AVOIDING DRAINAGE ERROR

Drainage error may be avoided by using torsional viscometers, but these instruments are outside the scope of this paper. In the Lidstone viscometer, previously referred to, the liquid to be tested rests upon mercury, and the separation of the two liquids would

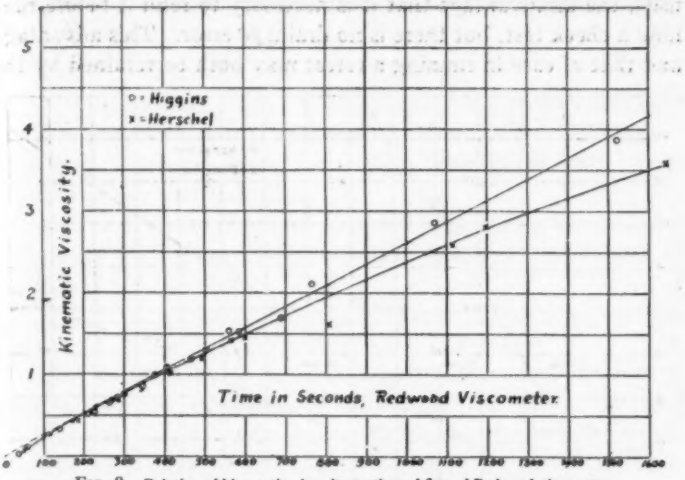


FIG. 8. Relation of kinematic viscosity to time of flow of Redwood viscometer

apparently offer considerable difficulty. In technical instruments for oil, of which the Saybolt Universal and Furol may be taken as examples, there is no drainage error, but there is another error, due to the contraction of the oil after it leaves the outlet tube, which may be called the cooling error. Barbey avoids both the drainage and the cooling errors by using a constant hydrostatic head, and running a test for the constant time of ten minutes. The receiving flask is heated in the bath to the nominal temperature of test, before reading of the volume discharged is taken, and results are expressed as "fluidity" or the rate of discharge in cubic centimeters per hour.

Bingham[18] suggests that the drainage error may be avoided in his instrument if the flow begins in the neighborhood of the trap

[18] E. C. Bingham, Fluidity and Plasticity, p. 66; 1922.

opening, for then a certain amount of liquid may flow into the measuring bulb after the record of time has begun, and this will tend to offset the effect of any liquid left in the bulb at the end of the time of flow.

The Ubbelohde form of Ostwald instrument has, as ordinarily used, the disadvantage that it is necessary to refill it before running a check test, but there is no drainage error. This advantage and that of ease in running a retest may both be retained by the

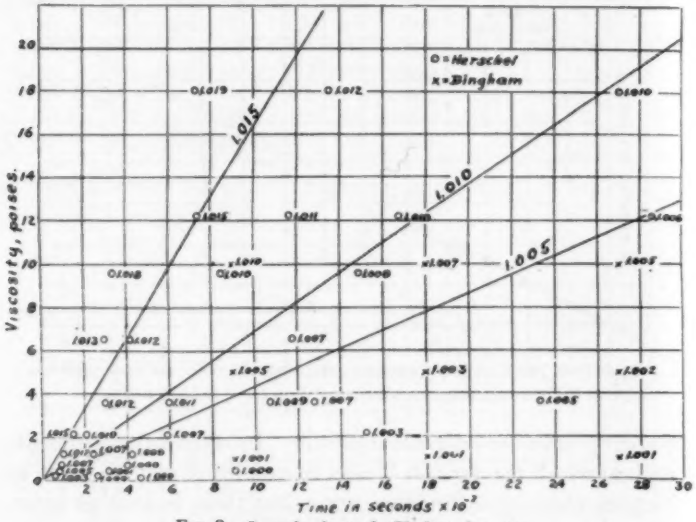


FIG. 9. Correction factors for Bingham viscometer

following slight changes. Referring to Fig. 1, graduate bulb K with marks similar to B and D. Fill from A to H, keeping the bulb K dry, and empty the trap. Apply air pressure on the left limb and make the first run into the dry bulb. Apply air pressure on the right limb and make the second run into bulb C which will be wet, and the third run will be into bulb K which will also be wet. The difference in the time for the first and third runs will be due to drainage error.

It should be noted that there is normally a difference in time between a run from left to right and one from right to left, so that

the difference in time between the first and second runs would not usually be due entirely to the drainage error. The drainage error could however be calculated as the per cent difference between the viscosities as calculated from the first and second runs, the instrumental constant $h'$ allowing for the difference in time of flow in the two directions when the volume is measured both times in a wet bulb.

## 9. CONCLUSIONS

1. The drainage error is negligible only for comparatively light oils when a sufficiently long time is taken for the discharge. A diagram is given to show the relation between viscosity, time of flow and per cent drainage error.

2. The drainage error may be avoided by having the trap on the opposite limb from the bulb which measures the volume discharged.

## APPENDIX. COMPARISON OF VISCOSITIES AS OBTAINED BY THE SCOTT VISCOMETER, AND BY THE PLUMMET METHOD OF BASSECHES[19]

The investigation to be described was undertaken in the hope of explaining the difficulty in calibrating the Scott viscometer, afterwards shown to be due to drainage error of the Bingham instrument used in determining the viscosity of the calibrating liquids. While the results are somewhat discordant, this may be attributed largely to the rapid change of viscosity with the temperature in the case of such highly viscous substances. Even with lubricating oils, an error of one per cent in viscosity, will be caused by an error of 0.2 to 0.1°C, depending upon the viscosity and upon the source of the crude oil.

While the tests were inconclusive as far as proving or disproving that there was a serious drainage error in the Bingham instrument, it is believed that a description of the Basseches method will be of interest since this method seems to be unsurpassed as a very rapid though approximate method of measuring the consistency of very viscous or plastic substances.

Basseches method is as follows. The liquid or soft plastic substance to be tested is placed in a shallow dish on a stand under a

[19] Based upon unpublished manuscript of J. L. Basseches, formerly of the Bureau of Standards.

plummet hung from the arm of a chemical balance the beam of which can be lifted. The plummet is of cylindrical shape with a conical base, the juncture of cylinder and cone forming the line to which the plummet is immersed by raising the stand. The beam is then lifted and if necessary the stand is readjusted so that the pointer comes to the first division on the right end of the scale. A weight is placed on the pan of the balance, causing the plummet to be pulled out of the material under test, and the time required for the pointer to traverse five scale divisions is taken by means of a stop watch. The pan also contains the counter-poise for the plummet. As will appear later, this operation must be repeated with a different weight on the pan, in order to find both of the numerical values determined by the test.

It will be assumed that two properties or groups of properties are to be measured, one of which, viscosity, causes a resistance in proportion to the velocity, or inversely as the time, while the second group of properties causes a resistance which is independent of the velocity. Let $W_v$ be that portion of the weight required to overcome viscosity, and $W_s$ the portion required to overcome the constant resistance. Then

$$W = W_v + W_s \tag{7}$$

Basseches regarded $W_s$ as a measure of surface tension only, believing that the "yield value" of plastic materials is only a form of surface tension manifested in the adsorbed liquid films on the surfaces of the solid particles. Without attempting to decide this matter, $W_s$ will be considered here as a measure of all other resistances than viscosity, which may include surface tension, yield value and friction of the balance. Part of the weight must also be expended in lifting the film which adheres to the plummet.

If all the weight were exerted in overcoming viscosity, t would be inversely proportional to W, or for two trials,

$$W_1 t_1 = W_2 t_2 = \text{constant} = V \tag{8}$$

where $W_1$ and $W_2$ are the weights used in the two trials, and $t_1$ and $t_2$ are the corresponding times, the units employed being grams and seconds. But since surface tension, or some similar resistance must also be overcome, the net weight expended in overcoming

viscosity, and which must be inserted in equation (8) is $W-W_s$ so that the equation becomes

$$(W_1 - W_s)\, t_1 = (W_2 - W_s)\, t_2 = V \qquad (9)$$

from which

$$W_s = \frac{W_2\, t_2 - W_1\, t_1}{t_2 - t_1} \qquad (10)$$

After $W_s$ has been found from equation (10), V may be found from equation (9).

Two terms which are used to indicate the consistency of printing inks are "tack" or "tackiness" and "length" and Basseches proposed that $VW_s$ should be used as a measure of the former, and $\frac{V}{W_s}$ as a measure of the latter.

Since V is proportional to the viscosity in poises, if the liquid is truly viscous, this method may be used to determine viscosity if the plummet is calibrated with a liquid of known viscosity. If $\mu$ is the viscosity of the calibrating liquid in poises, then

$$\mu = KV \qquad (11)$$

where $K$ is an instrumental constant.

For example a sample of sodium silicate gave the following results at 22°C (71.°6F) using the 3 centimeter plummet.

| $W$ in grams | $t$ in seconds |
|---|---|
| 1.874 | 6.0 |
| 1.904 | 5.0 |

Then $W_s = \frac{11.244 - 9.520}{1.0} = 1.724$ and by equation (9), $V = 0.90$. Since under the same conditions castor oil gave $W_s = 0.88$ and $V = 0.78$, and since the viscosity of castor oil at 22°C is about 8.34 poises, from equation (11), $K = \frac{8.34}{0.78} = 10.7$

In a comparison of the plummet method using another sized plummet, with the Scott viscometer, and with the falling ball method,[20] the results were obtained as shown in Table 6 and Fig. 10.

[20] S. E. Sheppard, Jour. Ind. and Eng. Chem., 9, p. 523; 1917; W. H. Gibson and L. M. Jacobs, Jour. Chem. Soc. London, p. 473; May, 1920.

The viscosity by plummet was calculated from equation (11) using a value of 65.7 for K as obtained with blown rape seed oil at 30°C.

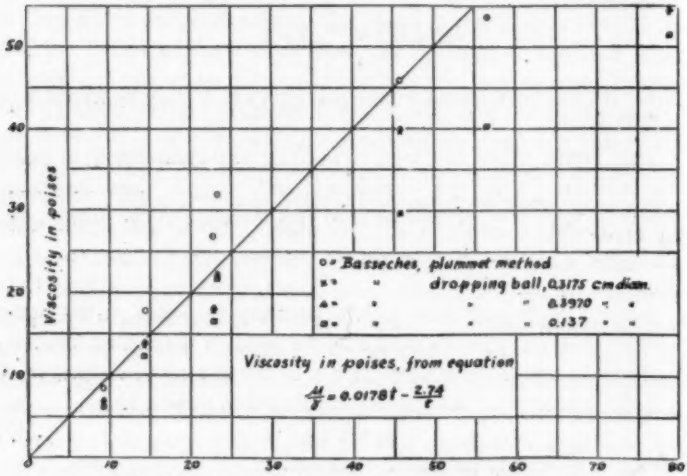


FIG. 10. Comparison of different methods of measuring viscosity

TABLE 6. *Comparison of different methods of measuring viscosity*

| Liquid | Temp. | Basseches | | | | | Herschel |
|---|---|---|---|---|---|---|---|
| | | V | Absolute viscosity, poises. | | | | |
| | | | Plummet | Dropping ball of diameter in cm. | | | Viscosity in poises by equation (6) |
| | | | | .3175 | .3970 | .137 | |
| | °C | Sec/g | | | | | |
| Castor oil | 23 | .128 | 8.4 | 6.7 | 6.9 | 6.3 | 9.3 |
| Burnt litho No. 1 | 30 | .270 | 17.7 | 13.5 | 13.8 | 12.3 | 14.4 |
| Burnt litho No. 1 | 23 | .408 | 26.8 | 17.9 | 18.1 | 16.5 | 22.7 |
| Rosin oil | 30 | .487 | 31.9 | 22.2 | 22.3 | 21.8 | 23.3 |
| Blown rape | 30 | .698 | 45.8 | 39.6 | 39.9 | 39.6 | 45.8 |
| Rosin oil | 23 | .817 | 53.6 | 38.4 | 37.9 | 40.3 | 56.6 |
| Blown rape | 23 | 1.15 | 75.5 | 54.2 | 54.6 | 51.4 | 78.9 |
| Half tone varnish | 23 | 5.00 | 328.0 | ..... | ..... | ..... | ..... |

BUREAU OF STANDARDS, WASHINGTON, D. C.

# SPECIFICATIONS FOR BOURDON TUBE PRESSURE GAGES FOR AIR, STEAM, AND WATER PRESSURES, AND FOR USE AS REFERENCE STANDARDS

BY
FREDERICK J. SCHLINK

This constitutes the second and concluding installment of specifications for recording thermometers and pressure gages begun in the September number of this JOURNAL. The specifications now presented cover pressure gages for ordinary service, and those for reference or test purposes. It is found desirable to differentiate the construction and accuracy requirements of these two types of gages in a number of respects, though common commercial practice has been to make the difference between them mainly a matter of richer appearance and of more detailed individual marking of graduations in the case of reference or test gages.

The other more important differences from common practice in these specifications are itemized in the introductory note preceding the first installment of the specifications, in the September number of this JOURNAL, to which reference should be made also for information as to the practicability and the use hitherto made of these specifications, the rationale of the statement of tolerance adopted, and the rather surprising precision that may be expected of good Bourdon tube gages under controlled conditions of use.

## SPECIFICATIONS FOR BOURDON SINGLE TUBE PRESSURE GAGES FOR STATIONARY SERVICE: AIR, STEAM, WATER

### 1. GENERAL

a. *Size.* The gage diameter as given in the order will be construed to refer to the available or effective diameter, that is, in the usual case, the smallest diameter of the bezel ring.

b. *Capacity.* The limit of graduation or capacity referred to in the order is the actual maximum working limit of operation of the gages, and the construction shall be of such rigidity and the parts so stressed, as to carry pressures approximating but

not exceeding the capacity pressure named, for an indefinite period if necessary, without permanent set beyond the limits of the tolerance hereinafter provided.

c. *Minimum Graduation.* The minimum graduation as called for in the order will require that at all parts of the graduated scale, the pressure equivalent of a single graduation interval shall be the same, and will be construed to prohibit the anomalous number and arrangement of graduations commonly and erroneously provided on pressure gages between the zero graduation and the first major graduation; provided, however, that the omission of all intermediate graduations between the zero and the first major graduation will be permitted; for example, in the case of a gage marked from zero to 80 lbs. by 1 lb., intermediate graduations between the zero and the 5 lb. graduation may be omitted at the option of the supplier.

d. *Marking.* Each gage shall bear the name of the actual manufacturer and a distinctive serial number, the latter to be legibly stamped, engraved or etched either upon the dial or the case flange, preferably the former.

e. *Items not Supplied.* The maker is not to supply gage cocks, nipples, or siphons.

f. *Delayed Rejection.* In case it is found expedient not to remove the dials and pointers of new gages at the time of the acceptance test, the purchaser reserves the right to return such gages at any later time for correction in case internal defects of such character are found as to make it certain that defective construction or workmanship existed in the gages at the time of delivery.

g. *Transportation Costs on Rejected Gages.* All costs of transportation on gages rejected for non-compliance with these specifications shall be borne by the supplier.

## 2. MECHANICAL CONSTRUCTION

a. *General.* These gages shall be of the bottom-connected type, of single-tube construction, with accurately cut and finished segmental gear and pinion. The linkwork shall be so arranged as to permit of general adjustment to correct multiplication and a secondary adjustment to correct for angularity of the linkwork connections.

b. *Mounting.* The mounting of the Bourdon tube and pointer mechanism is to be a single unit rigidly secured to the case. On gages of 500 lb. per sq. in. capacity or over, solder shall be employed only to secure tightness of joint.

c. *Permanence.* The materials and construction of these gages shall be such that a reasonable permanence of the initial adjustment will be maintained in service; gages which show any considerable secular change of the zero upon being placed in normal service or when given a reasonable oscillatory-pressure test within their rated capacity, will be returned for replacement. The materials are to be such that no corrosion interfering with the appearance or accuracy of the gage will occur in ordinary service.

d. *Linkwork—General.* Connections in the linkwork shall be either of the fork-and-pin type or shall consist of shouldered screws seated solidly in the members to which they are affixed. The length of the segmental gear and the properties of other elements of the movement, including the length of the hair-spring, shall be such that the pointer, in case of accidental overload, may move to the extent of 100% of the total graduated arc above the upper limit of graduation, and to the extent of 50% of the total graduated arc below the zero graduation, without in either case causing disengagement of the segmental gear and the pointer pinion.

e. *Links.* The connecting links used in the movement shall in no case be less than .05 in. in thickness, and bending of these links flatwise in order to obtain adjustment of the gage shall not be permitted.

f. *Gearing.* The segmental gear and pinion shall have working faces not less than .09 in. in width.

g. *Fit and Finish.* All spindles and bearings are to be neatly and accurately fitted, and excessive side or end shake will be deemed sufficient cause for rejection. The surface of the pointer spindle upon which the pointer is applied shall be smoothly finished and true in order that in adjusting the gage the pointer may be readily set in the exact position desired.

h. *Hair-Spring.* These gages shall be equipped with the usual hair-spring to minimize the backlash error, this hair-spring to be of a non-rusting alloy. It shall be so tensioned that at any reading of the pointer on the dial, it will be effective in eliminating backlash by turning the pointer pinion into contact with the mating gear teeth. The coils of the hair-spring must not at any position of the pointer within the interval of graduation, be in contact with other coils or with the parts of the gage itself except at the points where the spring is secured to the movement frame and to the pointer spindle respectively.

i. *Holes for Mounting.* The mounting flange shall have three uniformly spaced holes for attaching the gage to its support, one hole to be located at the top of the gage diametrically opposite to the pipe connection.

j. *Glass and Bezel.* The cover glasses shall be clear and free from visible blemishes; the means of securing glass in bezel and bezel to case shall be such that the case will be substantially dust tight.

k. *Type of Case.* These gages shall be supplied in flanged iron case with nickel-plated close bezel ring without ogee flare[1] (similar to figure —, page —, — Co's. Bulletin.—)

## 3. POINTER, DIAL, AND GRADUATIONS

a. *Range of Graduation.* The total range of graduation shall cover an angular interval of not less than 270 degrees.

b. *Graduations—General.* The dials shall be of nickeled or silvered metal, with permanent black graduations, deeply incised; numerals to be neat, simple in outline, disposed horizontally and entirely within the circle of graduations. The minor graduations shall not be less than .01 inch nor more than .02 in. in width. The major graduations shall not be less than two nor more than three times as wide as the minor graduations. The major graduations shall be suitably distinguished also by an increase in length over the minor graduations.

c. *Length of Graduations.* The length of the minor graduation lines, or the difference between the radii of the outside and inside graduation circles, shall not exceed the mean graduation interval; that is to say, the radial length of the minor graduation lines shall not exceed the mean center to center interval between these lines.

d. *Diameter of Outside Circle.* The diameter of the outside graduation circle of the dial shall not be less than 90% of the smallest diameter of the bezel ring, referred to in specification a, Section 1.

e. *Attachment of Dial.* The dial screws shall fit the holes in the dial accurately, with a diametral clearance not exceeding .005 in. and they shall also be snugly fitted as to their threads so that they may not be readily jarred loose by vibration. The

[1] This requirement relating to appearance only, is subject to modification to meet individual taste or the need of uniformity with other equipment.

manner of attaching the dial to the gage is to be such that it will be securely and permanently affixed.

f. *Pointer Clearance.* The pointer shall be so pivoted as to travel parallel to the dial, and the clearance between pointer and dial shall be not less than .03 in. and not greater than .09 in. at any point of the graduated scale.

g. *Shape and Length of Pointer.* The pointer shall be symmetrical about its longitudinal axis, shall be of neat appearance, and slender and sharp as to its index end. Its length shall be such that the index end will not entirely cross both circles limiting the graduation lines but will stop somewhat short of the outer circle, in order that, when desired, fractional intervals can be estimated.

h. *Stop Pins Omitted.* The gages furnished on this order are to be without zero stop pins.

### 4. ACCURACY

a. *Test Cycle—Tolerance.* These gages shall be calibrated and adjusted at a temperature of 80 deg. F.[2] approximately. The tolerance to be allowed in excess or deficiency shall not exceed one-half of one of the minimum graduations, as specified in the order, at any point within the range of graduation. The foregoing allowance of error is to include that due to friction and imperfect elasticity, the test being carried out, at the purchaser's option, without tapping or jarring the gage. The test to be performed will consist of a cyclic calibration through a range from zero to the upper limit of graduation and back to zero. Before the acceptance calibration is begun, the gage may be subjected to a pressure 25% in excess of its rated capacity, for a period not to exceed one hour, followed by a rest period not to exceed one-half hour.

## SPECIFICATIONS FOR BOURDON TUBE PRESSURE GAGES TO BE USED AS REFERENCE STANDARDS FOR TEST PURPOSES

### 1. GENERAL

a. *Size.* The gage diameter as given in the order will be construed to refer to the available or effective diameter, that is, in the usual case, the smallest diameter of the bezel ring.

b. *Capacity.* The limit of graduation or capacity referred to in the order is the actual maximum working limit of operation of the gages and the construction shall be of such rigidity and the parts so stressed, as to carry pressures approximating but not exceeding the capacity pressure named, for an indefinite period if necessary, without permanent set beyond the limit set by the tolerance hereinafter provided.

c. *Marking.* Each gage shall bear the name of the actual manufacturer and a distinctive serial number, the latter to be legibly stamped, engraved, or etched upon the dial. The units in which and the temperature at which the gage is calibrated shall be clearly marked upon the dial in the following form: lb. per sq. in. at 80° F.

d. *Items not supplied.* The maker is not to supply gage cocks, nipples, or siphons.

e. *Transportation costs on rejected gages.* All costs of transportation on gages rejected for non-compliance with these specifications shall be borne by the supplier.

### 2. MECHANICAL CONSTRUCTION

a. *General.* These gages shall be of the bottom-connected type, of single-tube construction, with accurately cut and finished segmental gear and pinion. The link-

work shall be so arranged as to permit of general adjustment to correct multiplication and a secondary adjustment to correct for angularity of the linkwork connections. In the gages as delivered, there shall remain not less than one fourth of the adjustment interval on each of the two adjustments referred to in this specification, to provide for carrying out readily such subsequent adjustments as may be required during the life of the instrument.

b. *Mounting.* The mounting of the Bourdon tube and pointer mechanism is to be a single unit rigidly secured to the case. On gages of 500 lb. per sq. in. capacity or over, solder shall be employed only to secure tightness of joint.

c. *Permanence.* The materials and construction of these gages shall be such that a reasonable permanence of the initial adjustment will be maintained in service; gages which show any considerable secular change of the zero upon being put into use or when given a reasonable oscillatory-pressure test within their rated capacity, will be returned for replacement.

d. *Linkwork-General.* Connections in the linkwork shall be either of the fork-and-pin type or shall consist of shouldered screws seated solidly in the members to which they are affixed. Smaller diameters and bearing lengths of spindles than those employed in the usual service gages are desired in these test gages since the conditions of service favor a much lower rate of depreciation, due to the less severe usage and handling than in the case of ordinary pressure gages. The segmental gear and pinion shall have a minimum working face consistent with reasonable durability, not less than .04 in. and not more than 0.10 in. The length of the segmental gear and the properties of other elements of the movement, including the length of the hair-spring, shall be such that the pointer, in case of accidental overload, may move to the extent of 50% of the total graduated arc above the upper limit of graduation, and to the extent of 25% of the total graduated arc below the zero graduation, without in either case causing disengagement of the segmental gear and the pointer pinion.

e. *Links.* The connecting links used in the movement shall in no case be less than .05 in. in thickness, and bending of these links flatwise in order to obtain adjustment of the gage shall not be permitted.

f. *Fit and Finish.* All spindles and bearings are to be neatly and accurately fitted, and excessive side or end shake will be deemed sufficient cause for rejection. The surface of the pointer spindle upon which the pointer is applied shall be smoothly finished and true, in order that in adjusting the gage the pointer may be readily set in the exact position desired.

g. *Hair-Spring.* These gages shall be equipped with the usual hair-spring to minimize the backlash error, this hair-spring to be of a non-rusting alloy. It shall be so tensioned that at any reading of the pointer on the dial, it will be effective in eliminating backlash by turning the pointer pinion into contact with the mating gear teeth. The coils of the hair-spring shall lie substantially in a plane and must not at any position of the pointer within the interval of graduation, be in contact with other coils or with the parts of the gage itself except at the points where the spring is secured to the movement frame and to the pointer spindle respectively.

h. *Glass and Bezel.* The cover glasses shall be clear and free from visible blemishes; the means of securing glass in bezel and bezel to case shall be such that the case will be substantially dust tight.

i. *Type of Case.* No special details of case design are required, but the screw bezel construction will be given preference. Either brass or iron cases will be accept-

able, but in any event the finish is to be of the best quality, with smooth surfaces, well japanned if of iron, and of neat appearance throughout. A narrow bezel ring without flare is preferred, and the glass should lie as close to the pointer as practicable.

## 3. POINTER, DIAL, AND GRADUATIONS

a. *Arc of Graduation.* The total range of graduation shall cover an angular interval of not less than 270°.

b. *Graduations—General.* The dials shall be of nickeled or silvered metal, with permanent black graduations, cleanly incised; numerals to be neat, simple in outline, disposed horizontally and entirely within the circle of graduations. The surface finish of the dial shall be such that clear marks and graduations can be made upon it with an ordinary lead pencil and that such marks can be easily erased if necessary. The graduations are not to exceed .01 in. in width and the major graduations shall be distinguished from the minor graduations not by an increase in width of line but by moderate extension of their length alone. The emphasizing and numbering of the graduations shall be upon a decimal basis and the fifth and tenth graduations rather than the second or fourth shall be emphasized.

c. *Length of Graduations.* The length of the minor graduation lines, that is, the difference between the radii of the outside and inside graduation circles, shall not exceed the mean graduation interval; that is to say, the radial length of the minor graduation lines shall not exceed the mean center to center interval between these lines.

d. *Diameter of Outside Circle.* The diameter of the outside graduation circle of the dial shall not be less than 90% of the smallest diameter of the bezel ring, referred to in specification a, Section 1.

e. *Attachment of Dial.* The dial shall be attached to the case or movement in such manner as to be securely and definitely fixed in position, independently of the friction under the heads of the holding-down screws, its accurate and permanent centering being assured either by accuracy of fit of the holding-down screws or by dowel pins.

f. *Pointer Clearance.* The pointer shall be so pivoted as to travel parallel to the dial, and the clearance between pointer and dial shall be not less than .03 in. and not greater than .05 in. at any point of the graduated scale.

g. *Shape and Length of Pointer.* The pointer shall be symmetrical about its longitudinal axis, shall be of simple design and neat appearance, and slender and sharp as to its index end. Its length shall be such that the index end will not entirely cross both circles limiting the graduation lines but will stop somewhat short of the outer circle, in order that when desired, fractional intervals can be estimated.

h. *Stop Pins Omitted.* The gages furnished on this order are to be without zero stop pins either on the dial or within the case, except that a special locking device capable of being disengaged at will may be provided in order to secure the gage against damage due to the shocks incident to shipment and handling.

## 4. ACCURACY

*Test Cycle—Tolerance.* These gages shall be calibrated and adjusted at a temperature of 80° F.[2] approximately, the naming of this temperature being necessary in

[2] Subject to variation to suit special requirements.

order to give definiteness to the meaning of the tolerance of error below. The tolerance to be allowed in excess or deficiency on the gages as delivered, shall not exceed one-fourth of one of the minimum graduations as specified in the order,—at any point within the range of graduation. The foregoing allowance of error is to include that due to friction and imperfect elasticity, the test being carried out, at the purchaser's option, without tapping or jarring the gage. The test to be performed will consist of a cyclic calibration through a range from zero to the upper limit of graduation and back to zero. Before the acceptance calibration is begun, the gage may be subjected to a pressure 15% in excess of its rated capacity, for a period not to exceed one hour, followed by a rest period not to exceed one-half hour.

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29 W. 39TH ST., NEW YORK CITY.

# A METHOD OF MAINTAINING SMALL OBJECTS AT ANY TEMPERATURE BETWEEN −180°C AND +20°C

BY
P. P. CIOFFI AND L. S. TAYLOR

In the determination of the crystal structure of solid mercury by X-Ray analysis,[1] difficulty was encountered in the formation of ice, condensed from the atmosphere around the tube containing the mercury. Since the presence of the atmosphere was not otherwise objectionable, a method was devised which may readily be adapted to any small object within the temperature range between −180°C and +20°C, by which the temperature may be maintained constant for many hours to within about 4°. The method consists in surrounding the object to be cooled by a stream of cold dry air, while keeping any surfaces exposed to the free atmosphere above 0°C.

The cold dry air is obtained by evaporating liquid air in a Dewar flask (Fig. 1) by an electric heater immersed therein. The cold air is forced by the pressure thus created past the substance under examination through a vacuum heat-insulated delivery tube. The design of the delivery tube may be varied widely depending upon the nature of the problem. If visual observation is not necessary, the whole delivery tube may be of silvered glass, and may extend beyond the point where the measurements are taken, thus minimizing the expenditure of liquid air. Where visual observation is necessary or where, as in the case of X-Ray analysis no crystalline material other than the substance being analyzed can be permitted to be in the X-Ray beam, the part of the delivery tube surrounding the substance may be of clear glass. To reduce X-Ray absorption, the walls of the tube in the path of the beam should be pyrex or borosilicate glass drawn very thin. Absorption may be reduced still further if the sample is small and

[1] L. W. McKeehan and P. P. Cioffi. Phys. Rev. (2), *19*, 444–446; 1922.

of streamline shape, by placing it just beyond the open end of the delivery tube. It is necessary that the cold air be conveyed across the substance as an unbroken stream, without mixing with the surrounding air, which is relatively warm and moist. The necessary conditions can be maintained for several diameters of the delivery tube beyond its open end by placing at this distance

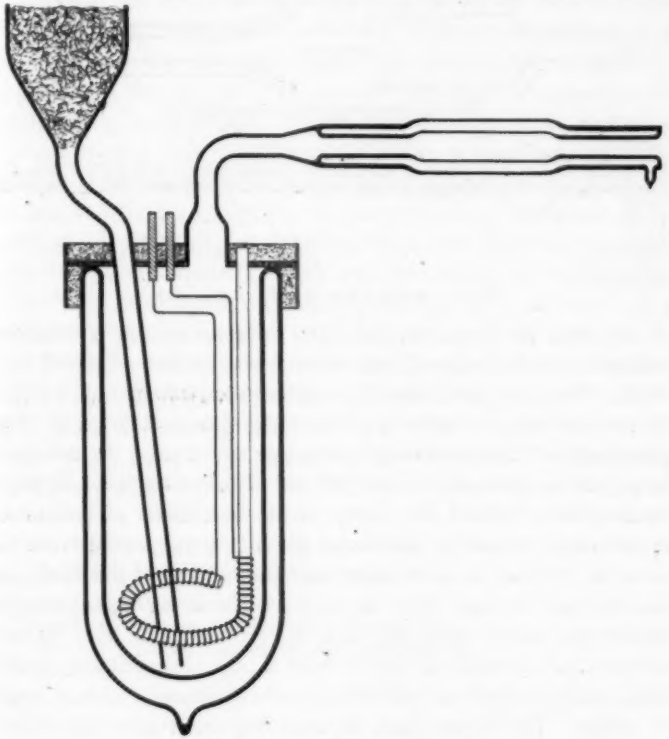

FIG. 1. Section of Complete Apparatus

the mouth of a tube connected to a rough vacuum pump of sufficient capacity (Fig. 2). This tube should have a diameter about twice that of the inner delivery tube, and a length about twice that of the gap. The connection to the vacuum pump must be warmed to prevent clogging by ice condensed

from entrained air. Flaring the mouth of the delivery tube preserves the integrity of the stream, and prevents fringes of frost from building across the gap. The vacuum heat insulated delivery tube may be vertical but where a horizontal section is required, the construction of the right-angled double walled tube (Fig. 3) is a matter of some nicety. If tubes over

FIG. 2. Arrangement for Cooling in Open Air

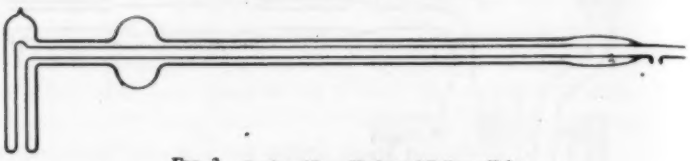

FIG. 3. Section of Long Horizontal Delivery Tube

25 cm long are required, flexibility of construction is necessary owing to the difference in expansion between the outer and inner walls. This may be obtained by including a flattened bulb section in the outer tube to serve as an expansion joint. The use of pyrex glass has here the additional advantage of reducing the difference in expansion between the two tubes. The heater is a coil of resistance wire with a low temperature coefficient of resistance. It is wound around a horizontal glass ring supported from the cover of the flask so as to hang near the bottom of the flask, and has its leads brought thru the cover. The cover makes airtight sealing-wax joints with the neck of the flask and with its connections, is conveniently made from a fibre disk suitably perforated, and is flanged on both sides by the addition of a short length of tubing. The Dewar flask requires frequent replenishment and occasional cleaning, both of which processes are facilitated by leaving it unsilvered. The flask is charged with liquid air by means of a funnel passing through the cover and reaching nearly to the bottom. This funnel is provided with a plug of glass wool for filtering out ice and solid carbon dioxide. In spite of this precaution particles of frozen impurities gradually accumulate and

finally make it difficult to observe the liquid air level, so that it becomes necessary to interrupt the experiment and clean out the flask. This is most easily done by maintaining a small current thru the heater, while passing air thru the system.

Temperature regulation is effected by changing the rate of evaporation of the liquid air, i. e., by changing the current thru the heater, and the mean temperature may be varied over a range from just below room temperature to a minimum depending upon the dimensions and heat insulation of the delivery tube. The regulation being electric can easily be made automatic if constancy of temperature is essential. Where considerable work is to be done covering a wide range in temperature, it is advantageous to make a temperature calibration of the apparatus in terms of the heater current, replacing the sample with a resistance thermometer of about the same dimensions and thermal capacity. In special cases the sample itself may be used as a thermometer, or the temperatures may be measured during the experiments by a thermometer adjacent to the sample. In a particular case, with a tube about 50 cm long and 1 cm inside diameter, a temperature of —150°C was maintained at the outlet with an expenditure of 94 watts in the heater, and this required a supply of about 2 liters of liquid air per hour. The maintenance of a constant temperature required the recharging of the flask when the level of the liquid air reached to within 3 cm of the heater. At this rate of boiling the system required cleaning about once in six hours which was therefore the limit for continuous operation.

RESEARCH LABORATORIES OF THE
AMERICAN TELEPHONE AND TELEGRAPH COMPANY
AND THE WESTERN ELECTRIC COMPANY, INCORPORATED
JULY 21, 1922.

# A TUNGSTEN FURNACE FOR EXPERIMENTS ON DISSOCIATION AND IONIZATION

BY
K. T. COMPTON

Requests have been received from several sources for a description of the tungsten furnaces in use in this laboratory for the investigation of radiating and ionizing potentials and for the excitation of spectra of dissociated diatomic gases. The accompanying sketch gives the details of construction of the furnace used by Dr. Duffendack in his work on low voltage arcs in hydrogen, nitrogen and iodine. The figure is drawn to scale.

The furnace is made of sheet tungsten, which may be obtained from the Elkon Works of the General Electric Company at Weehawken, New Jersey, in thicknesses down to 0.002 inch or less. A piece, cut to the right dimensions, is bent into the form of a cylindrical tube and clamped by the end pieces. Each of these consists of a small steel "napkin ring" fitting in the split rectangular steel block. The tungsten sheet is held between the "napkin ring" and the block. These blocks are mounted on water-cooled brass tubes, which serve as leads for the heating current. These leads pass into the surrounding glass or metal vessel through brass tubes which pass through the water-cooled brass end pieces (not shown). Short glass tubes surround the water-cooled leads for purposes of insulation. The tungsten tube furnace is encircled, at two or three points between the end blocks, by loops of fine tungsten wire drawn tight enough to prevent bulging of the tungsten sheet along the line of the cut. The central electrode is a straight length of 20 mil tungsten wire, welded to heavier molybdenum leads. By adjusting the length of this wire, it is possible to secure equal potential drops along the furnace and the filament, so that they act essentially as equipotential electrodes.

Although we have used steel clamps, molybdenum clamps would have been preferable, since the steel at the ring of contact melts

and alloys with the tungsten before the highest temperatures possible with the furnace have been reached. Molybdenum blocks can be machined to required dimensions and can be secured from the Elkon Works of the General Electric Company at a very reasonable price. We first tried seamless brass tubing for the water-cooled leads, but these invariably spring leaks after continued use, causing the burning out of the tungsten electrodes. This occurred even when the tubing was thoroughly "tinned" with

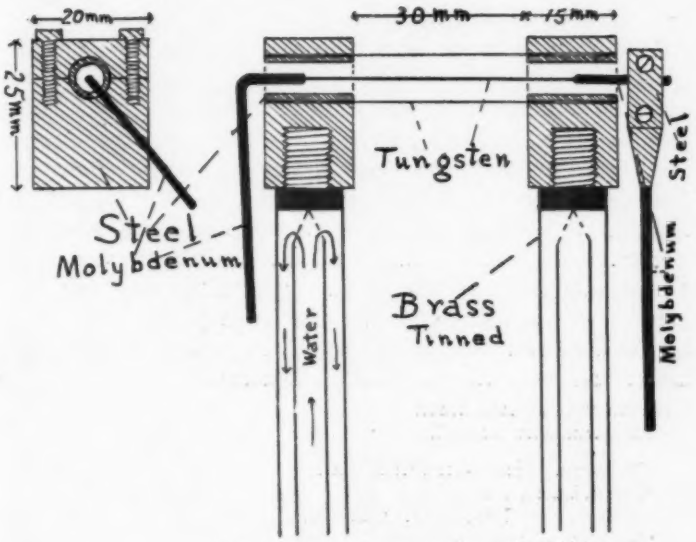


FIG. 1. Detail of Tungsten Furnace

solder, inside and out. With the outer tube bored out of solid brass rod and thoroughly "tinned," no appreciable leakage developed. The molybdenum leads to the filament were held in clamps and bent slightly so as to keep the filament under sufficient tension to prevent its sagging at high temperature. The temperatures of the furnace were estimated from its resistance, after making allowance for the resistance of the leads. The degree of dissociation of any gas in the furnace may be calculated by

means of Nernst's equation of the "reaction isobar."[1] if the heat of dissociation is known and if the chemical constant is known[2] or can be calculated.[3]

The furnace of the dimensions shown above required about 200 amperes, with a potential drop of 6 volts, to reach its melting point. It reached a good white heat with 100 amperes. We used storage batteries, but it should be possible to use a transformer, being careful that the phases of the heating currents in the furnace and the filament were equal, so as to insure their equivalence to equipotential surfaces.

In addition to its use in studying low voltage arcs, it has been used to investigate conditions of spectral excitation, observations being made through the open end of the furnace. By mounting parallel plates, alternately, positively and negatively charged, just beyond the open end of the furnace, ions may be prevented from passing from the furnace into the region beyond these plates. Another plate placed in this ion-free region so as to receive radiation excited within the furnace acts as a photoelectric detector of this radiation. By this means Dr. Olmstead and the writer have proved the excitation of the first four and the convergence members of the Lyman series in atomic hydrogen at the successively higher voltages 10.1, 12.0, 12.6, 13.0, 13.6.[4]

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[1] W. Nernst, "Theoretische Chemie."
[2] Nernst, loc. cit.
[3] Schames, Phys. Zeit. *21*, p. 41; 1920.
[4] Not yet published.